The Ore Magmas

Josiah Edward Spurr

J. B. Tyrrell

THE ORE MAGMAS

THE ORE MAGMAS

A SERIES OF
ESSAYS ON ORE DEPOSITION

BY

JOSIAH EDWARD SPURR

FIRST EDITION
SECOND IMPRESSION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1923

PRINTED IN THE UNITED STATES OF AMERICA

CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER X

Concerning Metallographic Provinces

This chapter treats of metallographic provinces, as exemplified in Arizona, where at several and distinct metallogenetic epochs notable amounts of copper have been deposited. Each metal has its individual and strongly marked concentration into certain spots on the earth's crust, some more markedly than others: thus, tin is more highly concentrated than tungsten, and tungsten than silver.

We must conclude from those metallographic provinces which remain marked at different metallogenetic epochs (such as that of Arizona), that each magma wave at an intrusive or revolutionary epoch acquires some peculiarity not originally inherent in itself on arriving at such a province—or, in other words, that it experiences (in the Arizona province) an addition of copper. This indicates a heterogeneous stable under-earth, deeper than the magma zone, which deep zone is a rich storehouse of metals.

There is a remarkable alignment of silver districts along a straight northwest line in North America, and its prolongation coincides with the rich silver belt of South America. In North America there are various other straight mineral zones of lesser persistence, some northeast and some northwest; these are believed to represent some geometrical blocking out of the metalliferous under-earth, and to be ultimately related to the geometrical forms of the earth's face.

THE MEANING OF THE TERM metallographic province is easily grasped. A geographic province is some portion of the earth that possesses a distinct geographic individuality from other parts; a physiographic province is one in which the physiographic features (the configuration of the earth's face) have an element of unity as distinguished from other regions; a petrographic province is one in which the igneous rocks possess a unity, a blood relationship, which marks out the province by itself; and a metallographic province is one in which the metals possess a unity, a blood relationship, distinctive of that

province. I believe that it was I who suggested this last term, which I find stands for a very useful conception. Previously, however, De Launay had used the term metallogenetic (or metallogenic) for epochs and provinces alike. I have used his useful terms in the discussion of epochs, which depend on earth crises, igneous intrusions, and the concomitant features which I discussed in the last chapter. But the relative distribution of different metals in certain parts of the earth's crust is a distinct and independent problem, and clarity demands that a term be used fitting this circumstance and individual to it; and by the clear analogy with terms like physiographic and petrographic, the term metallographic is evidently the conventional and convenient one.

In 1902, I referred to such provinces as metalliferous.[1] I observed: "If one accepts as a working hypothesis (as the writer has done) this theory that the unequal distribution or the relative concentration of the commoner rock-forming elements in certain parts of the earth's crust (giving rise to distinct petrographic provinces and rock-types) has been effected by magmatic segregation, one cannot avoid accepting the same theory for the less common rock-forming elements.

"If one accepts this for the distribution of sodium, potassium, aluminum, magnesium, titanium, and phosphorus, he must accept it for manganese, barium, chromium, nickel, strontium, lithium, chlorine, and fluorine; and if he applies it to these latter, he must extend it to tin, bromine, and cobalt; to lead, zinc, copper, arsenic, antimony, wolfram; to mercury, silver, bismuth, vanadium, tellurium, and thorium; to gold and platinum, and even to iridium, ytterbium, and germanium.

"Following this idea, and observing that some regions are especially rich in sodium, some in magnesium, and some in titanium (petrographic provinces), we should expect to find some especially rich in chromium, some in nickel, some

[1] *Trans.* A. I. M. E., May, 1902, Vol. XXXIII, p. 336.

in tin, some in lead, some in copper, some in mercury, some in gold, some in platinum, etc. This is well known to be the case, and these regions, characterized by special combinations or amounts of the rarer, especially the commercially valuable, metals, I desire to call *metalliferous provinces.*

"A metalliferous province does not necessarily coincide with a petrographic province, for the reason that I have already pointed out—namely, that the petrographic province and its contained rocks is classified solely on the basis of the commoner rock elements, while the rarer ones, by the distribution of certain of which *metalliferous provinces* may be distinguished, follow independent laws of segregation, which nevertheless may sometimes partly coincide with the laws of segregation of some of the commoner elements, by virtue of an affinity or preferential association between a rare element and a common one."

I enlarged on this conception in 1905,[2] changing the term to the more logical "metallographic province." In 1907,[3] I barely mentioned it in my paper, "A Theory of Ore Deposition," which was written very briefly and plainly to embody my conception of the origin of ore deposits, gathering together already known or proposed explanations of magmatic differentiation and ore deposition and the like and adding to these my own original conceptions, the most striking of which, the Zonal theory, I announced there for the first time. De Launay's conception of "metallogenic" provinces does not cover what I include under the idea of metallographic provinces. His definition of "metallogenic" provinces seems to be a geographical one—it is a term used to designate certain geographic provinces which are ore-bearing. For example, under the "metallogenic provinces of Asia," he enumerates[4] 1, Siberia; 2, the Urals; 3, the Caucasus; 4, Russia and Turkestan; 5, Asia Minor and the

[2] *Trans.* A. I. M. E., July, 1905, p. 968; *Professional Paper* 42, U. S. Geol. Surv., p. 276.

[3] "A Theory of Ore Deposition," *Econ. Geol.,* Vol. II, No. 8, Dec., 1907, p. 781.

[4] "Traité de Metallogenie." Paris and Liège, 1913, p. 265.

Ægean Sea; 6, India; 7, Malacca and the East Indies; 8, Tonkin; 9, South China and Japan. Each metallogenetic province is characterized by a different combination of metallogenetic epochs and of conditions of folding and erosion. Therefore it seems to me that his characterizations would be better if he used a combination of the terms "metallogenetic epochs" and "metalliferous provinces." De Launay tends to find a similar development in all these metalliferous provinces, where ore has been introduced at one or more metallogenetic epochs, and this is revealed by the varying depth of erosion, exposing different types of veins formed at different depths: namely, the deep veins, the intermediate veins, and the superficial, which is much like the classification later followed by Lindgren.[5] Also, the vein type, as De Launay describes it, depends on the nature of the magma. Among veins of the "deep type," one finds, associated with granitic magmas, tin, gold, and copper; with basic magmas, copper and nickel (chromite, titanite, and magnetite, within the basic igneous rock itself). In veins of the "intermediate type," associated with dikes, occur especially lead and zinc. In veins of the "superficial type," associated with eruptive rocks, occur complex sulphides with silver and gold. Most superficial of all are deposits like mercury.[6]

All this is excellent, and quite conformable to my thought and other current thought. But the main idea that I am trying to dwell on in this present chapter is the wondrous segregation of certain metallic elements into certain limited fields of the earth's crust, each according to its own inscrutable law. We have considered the principle of metallogenetic epochs in the preceding chapter: the geographically classified ore-bearing districts or provinces (metalliferous provinces) we shall have constantly to consider, and I think they merit no special chapter in a book dealing with

[5] "Mineral Deposits," McGraw-Hill Book Co., New York, 1919.
[6] "Traité de Metallogenie," 1913, pp. 247, 251.

questions of origin; but the investigation of metallographic provinces is going to lead us into fields as yet untouched.

While the existence and theoretical and economic importance of these metallographic provinces has continually grown upon me, I am no longer quite willing to subscribe to the belief that they owe their origin to magmatic differentiation, as we understand the term. In this my earlier assumption I followed, I believe, the thought of Iddings, who suggested such an origin for petrographic provinces. I do not recall that he or other petrologists have advanced this thought further, however. I have come to suspect this conception as an unwarranted tangential leap, with the momentum gained by sound conclusions concerning magmatic segregation or differentiation on a smaller scale.

As I have observed before in this book, the record of segregation of a magma into portions locally differing from one another chemically and mineralogically, by drawing together into groups of the original constituents, is illustrated with diagrammatic clearness on many an outcrop. It is, as President Cleveland said concerning a political matter, a condition that confronts us—not a theory. Moreover, there has been abundantly well traced on a larger scale, by comparing the different portions of an intrusive dike, sill, or mass of igneous rock, which was manifestly introduced as a homogeneous magma (since the final variations bear a definite relation to the fortuitous final shape of the intrusion), a frequent process of pre-consolidation migration of certain elements of the magma into groups, producing on a larger scale distinct chemical and mineralogical variations in the crystallized rock.

Not so absolutely diagrammatically proved as the above, but of sufficient circumstantial clarity to be quite satisfying to the geologist, is the splitting up of magmas, such as granitic magmas, into components differing widely in composition, which are later intruded and crystallized as dikes of "complementary" composition, as, for example, very basic and very siliceous dikes (such as diabase and alaskite),

which by their close connection in point of age and localization, and their plain chemical and mineralogical relation with some body of intermediate rock, show quite satisfactorily to the careful and experienced student of the field that these different magmas have originated by differentiation, before intrusion.

As I have described in Chapter IV, the succession of lavas in many volcanic regions, such as in Nevada, corresponds with the theory of such a magma splitting on a very large scale into complementary types, as an andesite into rhyolite and basalt.[7] But the evidence is, as I have mentioned in Chapter IV and earlier writings, that this differentiation took place only after the ascension to the subcrustal region of a fresh supply of the parent magma, and this general idea has also been advocated by Sir Archibald Geikie and Dr. J. P. Iddings. During the Tertiary in Nevada,[8] as I have described, such complete cycles of differentiation, in which andesitic magma was repeatedly differentiated into similar rhyolites and basalts, took place one after the other; and were probably three or four in number. In order to get a more vivid, even though rough, picture of the geologic time concerned in the process, if we assume Barrell's estimate of 60,000,000 years for the Tertiary, the average of each cycle of complete differentiation would not be more than 15,000,000 or 20,000,000 years—not at all, relatively and geologically speaking, a vast period of time. Applying the erosion scale (based on the figure, earlier taken, of one foot in 5,000 years[9]), the cycle of magma differentiation occupies in this instance the same period as the stripping off by erosion of 3,000 or 4,000 feet of rocks. This evidence of active differentiation from repeated accessions of intermediate magma, which apparently was all derived from one general source, and which previously had evidently

[7] J. E. Spurr: *Jour. Geol.* "Succession and Relation of Lavas in the Great Basin Region," Vol. VIII, pp. 621-646.

[8] See Chapter IV, pp. 228, 230.

[9] See Chapter IX, p. 414.

undergone no differentiation, I took to indicate that only under special conditions did differentiation take place, and that those special conditions were characteristic of a relatively elevated position in the crust (to which the new supplies of intermediate magma were successively introduced); and that they did not obtain at the source or reservoir, where the common magma was held under fixed conditions, due to temperature or pressure, or both.

This would imply a normal lack of differentiation, in the sense that we understand it, at the ultimate source whence the invasions of igneous magma are derived; and would negative the hypothesis of universal processes of differentiation, as we understand the term, such as would account for the differences between one petrographic province[10] and another. Moreover, we have, so far as I know, no direct evidence whatever tending to indicate that the chemical differences which distinguish one petrographic province from another have had this origin. Indeed, there is no evidence that they have any secondary origin whatever, or anything to dispute the assumption that they are primary, so far as concerns our conception or thought as to the state of the world's crust throughout what we commonly call geologic time.

It is widely held that the ocean basins as major features have been basins throughout the geologic record, and that the general continental areas have been in a general way continental areas since the dawn of geologic history: in other words, that the greater depressions and the greater swellings of the crust have been, relatively speaking, stable. Examination of the rocks of the continental areas, and of those of the ocean areas, has shown that the latter have markedly greater specific gravity. This has also been determined by pendulum measurements, and recently Dr. H. S. Washington has supported it by a compilation of

[10] This term as I use it has a different significance from the comagmatic province of Iddings, Washington, and others, who used it to signify provinces in which the different igneous rocks are derived from a common magma.

all available igneous rock analyses.[11] Therefore, the land and sea areas in a general way represent great contrasted petrographic or magmatic provinces, which have maintained their differences throughout the record which has been deciphered. On a smaller scale, also, we find that this is true. The region of the Great Lakes is one of great crustal density, as pendulum measurements show; and it was so in pre-Cambrian times, when basic lavas were abundantly ejected in the Keweenawan, and vast sedimentary iron deposits were successively laid down at different periods. The basin of Lake Superior was a basin then as now—a natural hollow in the earth's crust, due, apparently, to its greater weight.

Considering the earth as a whole, we find that the rarer metals are distributed very unequally, and occur especially in certain provinces, which may accordingly be designated as metallographic provinces. Tin is a good example. Absent, except sporadically and in small quantities, in North America, it occurs in an important province in Bolivia, in South America, but not in South America outside of this province. Another important province lies in the Malay Peninsula and the Dutch East Indies and adjacent regions. This Asian-Australasian zone or province, which extends from Australia to China, produced, in 1918, 70 per cent of the world's tin; while Bolivia produced over 21 per cent, leaving less than 9 per cent for the rest of the world.[12] Smaller provinces occur, which are quite as strongly marked and individual, such as that of western Europe, exhibited principally in Cornwall and Portugal.

Tin is always closely associated with siliceous igneous rocks, especially granites, and never with those of the basic kind, in which clear choice it differs from many minerals, such as copper, which is found associated with igneous rocks

[11] *Journal of the Franklin Institute,* Dec., 1920, Vol. 190, pp. 757-815.

[12] "Political and Commercial Geology." McGraw-Hill Book Co., 1920, p. 321.

of all degrees of basicity. It (tin) is among the final products of the granitic crystallization, and the residual magma which deposited it was rich in fluorine and boron; hence tin (nearly always as oxide, cassiterite) occurs in pegmatites and pegmatitic quartz veins, as well as more ordinary fissure veins, associated with minerals like topaz and tourmaline, containing the gaseous elements above mentioned. The ores occur usually very near or at the granite contact, and chiefly above or near the upper portion of a granite mass, but not to such an extent in the lower portions, showing that the tin-bearing residual magma solution ascended from and through the granite to near its upper contact, where the lower temperature caused it to condense.

But there are vast quantities of granite rocks all over the world that are not associated with tin. The tin granites, then, are a very special type, of limited geographical occurrence.

Tungsten is a common associate with tin, but the two are far from inseparable; witness the various fairly important tungsten-bearing provinces in the United States, nearly all of which contain no tin whatever. Like tin, tungsten is always connected with granitic rocks, occurring sometimes in pegmatites and pegmatitic quartz veins, and is similarly a final product of magmatic differentiation; but its association with minerals containing gaseous elements, like topaz and tourmaline, is not especially marked, as is the case with tin. Again, it is far from true that all granitic rocks are accompanied by tungsten deposits. In one broad aspect, however, tungsten resembles, in its distribution, tin. Mr. F. L. Hess says:[13]

"The world's large tungsten fields are grouped along the shores of the Pacific Ocean—not always close to it, but somewhere in the great mountain masses paralleling its margin, and the western shore is much richer than the eastern shore. In 1918, fully 92 per cent of the world's tungsten came from the shores of the Pacific, 61 per cent coming

[13] *Op. cit.*, p. 147.

from Asia, Australia, and Oceania, and 31 per cent from North America and South America. There is only one considerable tungsten-bearing area not situated close to the Pacific, that of the Iberian Peninsula, mostly in Portugal but partly in Spain. Of the less than 8 per cent not produced around the Pacific that area yielded nearly 5 per cent."

Summarizing the various tungsten-bearing provinces, or subprovinces, Mr. Hess observes that by far the most important region is in southeastern Asia, the second in Bolivia, Peru, Argentina, and Chile; and a close third the United States and Mexico.

It will be observed that tin is commercially absent, though sporadically present, in this third province. It appears, therefore, that the tin-bearing provinces are more closely concentrated than is the case with the closely affiliated tungsten. Yet tin is a more abundant element in the earth's crust, being rated thirty-third in abundance, while tungsten is rated thirty-eighth.[14]

Silver is rated as less abundant than tin, coming thirty-seventh on the list, but, as is well known, its occurrence in commercial form is very widespread, and nowhere is it concentrated in any especial province to the same degree as are the two typical minerals above mentioned. Yet silver also is by far most important in the great peri-Pacific major metalliferous province, which margins the Pacific. Unlike tin and tungsten, however, which are most abundant on the western side of the Pacific, in southeastern Asia, silver is by far most abundant on the eastern side, in the Cordilleran region of North and South America, which produces 73 per cent of the world's total,[15] while the western side of the Pacific contributes only 12 per cent. In this region, silver is associated with igneous rocks of various composition, from

[14] H. S. Washington: *Journal of the Franklin Institute.* Dec., 1920, Vol. 190, p. 777.

[15] F. S. Paine: "Political and Commercial Geology." McGraw-Hill Book Co., 1920, p. 499.

intermediate to siliceous. The silver-bearing metallographic provinces do not, therefore, coincide with those of either tungsten or tin, and are not so closely concentrated as are tungsten and tin. Yet all these minerals are in places derived from a common source and occur associated, as in Cornwall, and to a marked degree in Bolivia.

Silver, again, is closely associated with lead. The "by-product silver," which is principally silver associated with lead, is estimated at 47 per cent of the world's output, while the rich silver deposits (often associated with gold) constitute 53 per cent.[16] That lead can occur without silver is shown, for example, by the lead-zinc region of the Mississippi Valley, with the greatest concentration in Missouri. On the other hand, directly north of the Mississippi Valley, in Ontario, in the Cobalt, Keweenaw peninsula, Sudbury metallographic province, silver occurs, in places very highly concentrated, in a region where lead is rare.

Gold, again, one of the least abundant elements quantitatively in the earth's crust (rated forty-first in the list), is distributed very widely; in a way, indeed, that is phenomenal, compared with the other rare elements. Gold appears associated especially with the more siliceous igneous rocks, and is associated with granites as an end product of their differentiation, as I have shown[17]; and in this respect it is like tin and tungsten; but gold also occurs in connection with intermediate rocks, like diorites, which is not true of tin and tungsten. While tin and tungsten are each essentially confined to a single vertical rock zone, and that a deep, high-temperature zone, the deposition of gold occurs repeatedly at different zones and temperatures in the ascending column of ore deposition, and in notable commercial quantity in at least three places in the column: lowest in the gold-quartz veins of pegmatitic affiliations, as in California, Ontario, and the Appalachians; in pyritic (arsenopyritic) deposits, which represent an intermediate zone, of which

[16] F. S. PAINE: *Op. cit.*, p. 498.
[17] Chapter I, p. 64.

there are numerous examples; and in the shallow zone (p. 300). Therefore, gold deposits may be found in rocks which have undergone all degrees of erosion, which in part (but only in part) accounts for their wide distribution. Gold and silver are associated in many ores in many regions, but in the Cobalt metallographic province of Ontario, where the ores are closely associated with very basic igneous rocks of Keweenawan age, no gold occurs with the abundant silver, showing the absence of gold, but not at all of silver, in the residues from these basic magmas. Gold is, however, very widespread and abundant in the adjacent pre-Keweenawan province of Ontario, further north, as quartz veins of the deep zone, associated with granite intrusives.

In this pre-Keweenawan Ontario province, which stretches north and west into Manitoba, copper deposits in the form of chalcopyrite, as well as zinc, occur associated with gold-quartz veins, and all are associated and dependent upon granite intrusives; while in the Keweenawan Ontario province, copper, as native copper and chalcopyrite, occurs associated with the basic rocks: showing the ability of copper, unlike gold, but like silver, to concentrate itself from either extreme type of magma.[18]

An interesting mineral to consider in this respect is vanadium. The recent (1920) organization of the American Vanadium Company, combining the ownership of the Peruvian and American deposits, and thus "cornering" much of the known supply of the world, is a striking testimony to the limited and highly concentrated commercial occurrence of this element. The ore is found in lesser quantities in Mexico, Europe, South Australia, Africa, and in a limited district of Central Asiatic Russia. The commercial deposits are, however, so far, confined to the Cordilleran belt of the Western Hemisphere, a part of the great peri-Pacific major metalliferous province; but, unlike the gold and silver of this province, it is not found on the western side of the Great Ocean. Moreover, note the restricted spots where it

[18] For a more complete discussion of this, see the succeeding Chapter, XI.

actually does occur in this Cordilleran belt, for it is by no means characteristic of the belt as a whole. In the United States it occurs in a metallographic subprovince "covering Southern and Southwestern Colorado, Southeastern Utah, and parts of Arizona and New Mexico."[19] In this region it coincides with the occurrence of uranium and radium. In Peru, it occurs principally at a single mine. Its principal occurrence in the United States area is in sandstone, with no associated igneous rocks; but in parts of this region it is a component of ores which contain also lead, copper, fluorite, etc. In Peru, the ores are associated with igneous rocks. Whatever the origin of the vanadium ores may be, it is plain, in considering their occurrence, that we have to do with sharply defined metallographic provinces of the earth's crust. It is curious and interesting to note that while the vanadium province in the United States coincides with an uranium-radium province, no production of the latter allied metals is reported from the highly productive Peruvian vanadium district. Besides the United States, Austria contains an important uranium-radium province; and, according to latest reports (1922), the Belgian Congo. Radium occurs in lesser quantity in Cornwall, Australia, and Germany, in the first-named place in association with the tin ores; whereas other and more important tin provinces are not reported as containing radium.

That each metal is individual in its choice of spots in the crust for its concentration, even though it has its affinities and in some cases chooses to coincide with the concentrations of other metals, is fairly obvious; and this is a principle which could be further illustrated, but which has been for the time being dwelt on long enough. Such individual behavior, now grouped, now separate, is apparently not readily explicable by present-day chemical laws alone, for by these laws, operating on similar material, such as a homogeneous underlying universal magma, the associations

[19] R. B. Moore: "Political and Commercial Geology." McGraw-Hill Book Co., 1920, p. 166.

would be more uniform. Nor are the general divisions of igneous rocks of very much value when we come to try to associate their chemical characteristics with those of ore deposits: why certain granites should be tin-bearing, while the vast preponderance of granites on earth are tin-barren. for example. The association of gold ore with granite is far more general than in the case of tin; but since both occur characteristically associated with siliceous rocks, why do not the two occur together? Not only do they not do so commercially, but they hardly touch mineralogically. Tin may occur associated with silver and with copper, as in Cornwall and Bolivia, and gold is often associated with these two same minerals; but tin and gold in general shun each other's society.

The phenomena on which I have just touched, of metallographic provinces characterizing certain zones, belts, limited areas, or even spots on the earth, and that independently in large measure of the distribution of granites, diorites, or diabases, rhyolites, andesites, or basalts (although closely associated in general with belts of igneous activity and crustal disturbance), can hardly be explained except by postulating a highly individualized distribution of the metals in that portion of the earth beneath or at the base of those rocks which are exposed to our view by erosion, or beneath what we conveniently though perhaps inaccurately term the crust.

For this there is no better illustration available than the remarkable copper-bearing Arizona metallographic province. As noted in the last chapter, the copper in this province has been found in at least four distinct and widely separated geologic periods or metallogenetic epochs —the first, post-Algonkian and pre-Cambrian; the second, post-Permian; the third, post-Cretaceous; the fourth, late Tertiary. To picture the situation more clearly, if we again take Barrell's estimate of geologic time, something like 400,000,000 years elapsed between the epoch of the copper deposition in the Jerome district and that of Bis-

bee; something like 150,000,000 years between that of Bisbee and that of Clifton and Ray; and something like 50,000,000 years between the last named and the late Tertiary copper deposits. Yet at all these widely separated epochs the copper deposition was associated with, and was indeed apparently a phase of, the intrusion of intermediate to siliceous intrusives, together with folding and faulting. How shall we interpret it?

In the first place, we must recognize in this specific case, in Arizona, as well as for the general relations as above outlined in the world, that although at each epoch the ore deposits have been closely associated with, and even a phase of igneous rocks, the distribution of the ores and of the igneous rocks of the same period is a separate and distinct matter. This is most easily seen by considering the relatively recent epochs, concerning which more evidence is accessible. Take the copper deposits associated with late Tertiary lavas, for example: such lavas are not peculiar to Arizona, but have an immense distribution all around the Pacific, in a great belt, occurring all through the Cordilleran belt in North America, from the Rocky Mountains to the Pacific, and correspondingly in South America; yet only locally are they connected with copper deposits, as they are in the Arizona-New Mexico district.[20] Similarly, the post-Cretaceous copper deposits, so productive in Arizona, are associated with monzonitic and granitic intrusives which have a very wide distribution, over an immense territory in the United States and Mexico, yet are only conspicuously copper-bearing in certain spots, as, for example, in Arizona, at Butte in Montana, and certain areas in Northern Mexico.

A conjunction of causes seems to be here indicated. The universal igneous activity at certain periods, around the Pacific, testifies (as I have argued in previous chapters) to the outflowing from the ocean, and the inflowing to the

[20] Many of the great copper mines of South America and of Japan are associated with Tertiary intrusives.

land, and the upflowing into the crust, of a fairly homogeneous rock layer representing generally an intermediate to somewhat siliceous magma. This is the widespread and common phenomenon. Only when these waves of fusion or igneous flow reach certain regions, as, for example, Arizona, do they appear to have become phenomenally copper-bearing; and this we must explain by some local difference and peculiarity in this region, since it has persisted, in Arizona, through all the ages.

Considering the fairly uniform average petrographic nature of each of the peri-Pacific waves of fusion, such as that of the post-Cretaceous and that of the Tertiary, and, so far as we know, of the other great periods of revolution: we must conclude that in the Arizona copper-bearing metallographic province the petrographic wave must have acquired some additional peculiarity not originally inherent in itself, but inherent in this particular spot of the earth's crust—in other words, that in reaching this spot it has experienced an addition of copper. It follows that copper has been more abundant here than elsewhere on earth so far back in geological time as our reason can explore. It supports the hypothesis of an heterogeneous earth, whose heterogeneity originated at least far prior to the beginning of our geological record.

Such a conclusion must also be reached from the individual occurrence of the chief metallographic provinces which carry tin, tungsten, vanadium, and radium, as above outlined; each metal is a law unto itself as to distribution. That tin should occur mainly around the Pacific border, but predominantly on the western side; that tungsten should have a similar general distribution, yet not so predominantly on the western side; that silver and copper and vanadium should also occur mainly around the Pacific, but predominantly on the eastern side: points out this inherent earth-heterogeneity, independent of epochs of igneous intrusion or the general nature of the intruded and outpoured magmas. Yet the associations (character-

istically but by no means universally held to) of tin with tungsten, of vanadium with uranium, of lead with silver, indicate that the segregation of metals especially into spots in the earth's crust followed chemical law, and was not fortuitous; while the fact that these congenial metals, which have a preferential affinity for association one with another, are nevertheless clearly dissociated in certain metallographic districts, indicates at some period a very free and complete working out of chemical processes of segregation.

We glimpse a vastly ancient epoch in the world's history, when the fluid earth permitted on a grand and complete scale such segregations of the elements as are feebly reflected in the processes of magmatic differentiation in the igneous rocks of the superficial zone, as we know them. Yet the phenomena and the process by which they originated is a distinct problem, and it would be confusing to classify it with magmatic segregation as we can observe it. It is a process, as we may judge from the Arizona example, which was complete and came to a close long before the beginning of our record of cycles of magmatic differentiation in the region lying in and just beneath the superficial crust. Although it indicates an ancient pre-historic heterogeneity, it does not indicate an ultimately original heterogeneity, but an acquired one. It does not, therefore, support the planetesimal hypothesis, nor does it deny it, nor the nebular hypothesis; it does argue a geologically pre-historic epoch of high fluidity and opportunities for chemical segregation. What forces of segregation are going on in the sun at the present time?

And in this glimpsed stage and process, seen through the consideration of the present distribution of the rarer metals, and so pertaining to and explaining metallographic provinces, we get a corresponding light on petrographic provinces: more, we perceive that the ultimate explanation of the origin of the continents and the oceans, of stably heavier and stably lighter segments of the earth's crust,

reverts to this same pre-historic period and is subject to the same explanation, since the heavier and the lighter segments, which by reason of the difference in weight become hollows and humps, following that geophysical principle called isostasy, are fundamentally so on account of the unequal segregation of heavier and lighter elements.

Where, and at what depth, do these stably heterogeneous metallographic provinces of the earth lie? And by what means have the igneous waves acquired the indicated additions therefrom, which enable them to conform, in their products of magmatic differentiation, to the cast of the metallographic province? We have glimpses, by erosion, of the igneous magmas far down into the crust—to a depth of several miles—down to where they are undergoing differentiation—but we must conclude that these older stable elements must lie deeper—at a greater depth than any we have had access to—and represent a deeper zone than that of the igneous magmas as we know them.

We can thus reason out three zones which have to do with ore deposits: first, a superficial zone or crust of consolidated rocks; second, a deeper magma zone; and third, a still deeper zone, which, at least in metallographic provinces, as in Arizona, is a rich storehouse of certain metals. The lowest zone is a stable one, according to our definitions above. The superficial zone is stable in form, in that its rocks are not fluid, but solid; but unstable in position, in that it is pushed this way and that, and intruded by the violent movements of the magmas of the intermediate zone, and by other causes. And the intermediate or magma zone is stable neither as to form nor as to position. It is fluid, at least partly or largely; it is restless and changes its position, moving both laterally and vertically—sideways and up, never down; it undergoes differentiation. This fluid layer in the sandwich is, therefore, the great stabilizer, performs the observed physical and chemical adjustments, is the agent which ultimately renews the continents after the attacks of erosion, erects the mountains, supplies the igne-

ous intrusions, manufactures chemically diverse magmas, and forms the ore deposits. It does the work of the crust, so far as we can trace that work during the period of historic geology, and so far as that work is not done by the uppermost unstable zone, the gaseous atmosphere. Like the atmosphere, its unstable condition and its facility of movement are due largely to the concentration of gaseous elements which it contains.

In this intermediate fluid or magma zone, we can make a subdivision into two lesser zones: the zone of differentiation and crystallization; and the zone of chemical stability but spacial instability—that is, the deeper zone where the magma flows, but does not differentiate. These two subzones are clearly indicated by phenomena earlier referred to, which imply that cycles of differentiation are set up by the passage, into a zone favorable for differentiation, of successive supplies of a magma whose uniform nature at the repeated periods of replenishment shows that it has remained chemically stable, although potentially fluid.

The conjunction of causes which produce notable ore deposition may then be recapitulated, bearing in mind, as a concrete example, a certain metallographic province, such as the cupriferous province of Arizona and vicinity. At the base we have a stable earth-substance, extraordinarily rich in copper, as compared with the same zone in other geographic sections. Above is the zone of igneous flow and invasion, along which the fluid magma travels by waves or pulses, at the long-separated critical intervals when the continent, unbalanced by erosion, finally induces migration of subcrustal material to restore the balance, or when the telluric pressure of the subcrustal accumulations beneath the ocean initiates a flowage landward, or when both causes operate in conjunction to start the landward current. This is the act that unlocks the treasure house of copper (and other metals); evidently the arrival of the overlying magma produces conditions which release from stability or inertia some presumably small portion of the store—it must be a

small portion, for succeeding waves may have the same effect and acquire the same addition. The addition must originate along the line of contact—the line, which may or may not be approximately definite, of the fluid magma zone and the primeval zone beneath. It may be that the elements of the magma zone operate to take a certain amount of the encountered metal-rich earth-substance into solution, and so transfer it to the composition of the magma. At any rate, by this contact or conjunction the magma becomes thus locally phenomenally copper-rich.

The copper-bearing magma then awaits that crisis of balanced physical forces, in the crust above, which enables it, or a portion of it, to ascend into the zone where magmatic differentiation takes place. The third stage then arrives, that of the separation of the magma into various phases, among which the ore magmas represent one of the extreme types. Finally, comes the further ascension and intrusion of the various phases of the magma—stock, mass dike, vein, and flow—into various portions of the rigid upper zone, or crust; and there are finally injected the specialized ore magmas, and the copper deposits as we know them are formed.

The above is a definite conception, and according to it these different zones must occur at definite, although varying, depths. The earth that we know and can study is only that relatively superficial section that is exposed by erosion. The deepest erosion, presumably, is shown in those areas which have been land masses since pre-Cambrian time at least, and so have been continually subject to erosion—as, for example, in the Archæan region of Canada, north of the Great Lakes. If we assume a rate of erosion of a foot in 5,000 years, and the post-Archæan time period assigned by Barrell on the basis of relatively recent studies of radioactivity, of 620,000,000 years, we arrive at a total of 124,000 feet, or something over 23 miles, as the approximate maximum that could have been removed by erosion. But as this land mass existed for an indefinite period before the

Cambrian, the amount might be larger; possibly, speaking very roughly, twice as much. Of course, this vast amount, or even a very much smaller estimated amount, has been balanced from below by the flowage, beneath this ancient island, of the fluid magma layer which underlies the crust. At any rate, some of the rocks which we now study in parts of that region may well have lain at one time as much as say 25 to 50 miles deep; and we nowhere find (so far as I know), here or elsewhere on the earth, plutonic igneous rocks which have not risen from below. What the lower limit of the fluid magma zone may be is, therefore, conjectural, but it apparently may well be a multiple of the figures above given;[21] and, still below this, comes the stable primeval zone which is the permanent storehouse of the metals.

The fact that the average density of the earth (5.55) is far greater than that of the known crust (2.77) has led[22] to the assumption that either the interior is composed largely of the heavy metals, or that the internal earth matter is in a gaseous state, highly compressed by the pressure of gravity. Recent studies[23] have tended toward the view that compression cannot be the cause, and that,

[21] According to J. F. Hayford's geodetic surveys, the excesses of mass composing the continents and mountains are completely compensated by deficiency of density below, and this deficiency of density extends to a depth of something like 60 to 150 miles. Hayford's lower limit of deficiency of density would correspond to the bottom of the fluid magma zone which I postulate. Hayford's conception of isostasy (which has by no means been universally accepted by geologists) is substantially the one that I have adopted as a basis for my own conception; but while Hayford, as I understand it, visualized only a nice and compensating balance between erosion and subcrustal landward flowage, I have (necessarily) added to this the equally important factor of telluric (principally gaseous) pressure resident in this subcrustal fluid layer. I believe that consideration of this second factor will eventually explain what hitherto have been the unanswerable objections of geologists to the theory of isostasy. For example, the valid criticisms of Professor Harmon Lewis (*Jour. Geol.*, Vol. XIX, No. 7, Oct.-Nov., 1911) are, I believe, answered by a consideration of the operation of this telluric-pressure factor.

[22] H. S. Washington: *Journal of the Franklin Institute,* Dec., 1920, p. 757.

[23] *Op. cit.*, p. 784.

therefore, the heavier materials must occupy the center; and that the change to heavier materials as the center is approached is progressive. What this heavy interior earth-substance may be is suggested by the "shooting stars" or meteorites, which fall upon our earth from the immense spaces through which they travel—lost fragments of rock wandering nowhither. Their shape indicates that they have been broken asunder from larger bodies, and they are composed invariably of heavy materials, unlike the commoner rocks of our earth's crust. They are often simply an alloy of metallic iron and nickel, and in other cases contain iron-bearing silicates, such as olivene, which are characteristic of very basic rocks in the earth's crust. Moreover, such basic rocks on earth contain diamonds; and these have been found in meteorites. In Greenland, and in Spain, Russia, and elsewhere,[24] native iron (not alloyed with much nickel) has been found in basalts. From all this an analogy between subcrustal earth-substance and the substance of those bodies of which the meteorites are fragments has been inferred; and it has been reasoned that if the earth should fly into pieces, the nature of these pieces is revealed by the iron-nickel blocks which come hurtling into our atmosphere.

De Launay,[25] in an interesting discussion, calls attention (as many others have before him) to the shape of the earth and other heavenly bodies, which are spheroids flattened at the poles, as indicating a once fluid state, during which centrifugal force tended to increase the bulk at the equator. He further points out the tendency of centrifugal force and gaseous repulsion, in the fluid condition of these spheres, to scatter the elements of light atomic weight to the outside, or to the peripheral zones. Thus the moon has lost its volatile elements and its water. The sun contains in its main outer portion iron, magnesium, nickel, lime, alumina, soda, hydrogen, and helium, and traces of manganese, cobalt, titanium, chromium, and tin. De Launay calls attention

[24] H. S. Washington: *Op. cit.*, p. 788.

[25] "Traité de Metallogenie." Paris and Liège, 1913, p. 5.

to the fact that the earth is a magnet, and refers this magnetism to a ferruginous interior; and reasons that the position of the magnetic poles indicates that the crust of lighter, more siliceous, less ferruginous rocks is thicker at the equator than at the poles. He observes that the order in which metals characteristically occur as to relative depth agrees more or less with their atomic weights, and states the theory: "In the incandescent earth, before its solidification, the chemical elements have been removed from the center, inversely to their specific gravity, as if the atoms, dissociated and free of all chemical combination and at very high temperatures, had been separately and individually submitted to the universal attraction and to the centrifugal force."[26] In support of the thought that the present arrangement of elements indicates this early process, he defines certain zones as follows, giving the atomic weight of each element:

1. The primitive and peripheral atmosphere: hydrogen (1); helium (4).
2. The atmosphere: carbon (12); nitrogen (14); oxygen (16).
3. The siliceous crust: sodium (23); magnesium (24); aluminum (27); silicon (28).
4. The "mineralizers": phosphorus (31); sulphur (32); chlorine (34).
5. Basic segregations in depth: titanium (48); vanadium (51); chromium (52); manganese (54); iron (56).
6. Contact deposits and veins in basic rocks: nickel and cobalt (59); copper (64).
7. Mineral veins: zinc (65); molybdenum (96); silver (108); tin (118); tungsten (184); gold (197); mercury (200); lead (207); bismuth (208); radium (225); uranium (239).

Whatever vital truth there may be in the above summary, let us keep in mind the fact that the distribution of the metallic ore deposits as we find them certainly has little or nothing to do with specific gravity, or the depth from the surface; as, for example, gold (197) occurs at various zones of deposition, from the very deep to the very shallow,

[26] *Op. cit.*, p. 25.

while tin (118) is more characteristic of the deep zone only. Also, lead (207) occurs closely associated and characteristically higher than zinc (65), while zinc occurs above copper (64). Mercury (200) occurs only very near to the surface, as universally pointed out by geologists. No further illustration is needed to show that the vertical distribution of ore deposits is not by atomic weights, but depends on solubility in magma fluids and relative volatility or differential gaseous tension. And incidental to this proof, the study of ore deposits and allied vein phenomena shows that the distribution of silicon is due to the same agencies; and, extending the study to pegmatitic veins, that the distribution of potash, soda, and other elements is partly so determined. The accumulative importance of these chemical-solution and differential vapor-tension factors in determining the relative siliceous composition of the earth is not to be even approximately evaluated, but is at least important, and possibly preponderating, for the two outer zones—the crust and the underlying magma zone.

It is, however, probably a fruitful subject for speculation to consider the theory of arrangement according to atomic weight or specific gravity, in the original formation of the globe, and, therefore, in that portion which, stable and unchanged, we have deduced as underlying the magma zone; which anciently stable portion is locally at least rich in certain metals, and apparently constitutes the fundamental factor for a strongly marked metallographic province. In considering this let me refer again to the paper of Dr. H. S. Washington. He points out that, among the elements, those which are characteristic of, and most abundant in, the igneous rocks ("petrogenic" elements) are of low atomic weight, and occur normally as oxides, silicates, chlorides, and fluorides; and that those which occur as ores are of high atomic weight ("metallogenic" elements), and occur in nature as "native" metals, as sulphides, arsenides, bromides, etc., but not primarily oxides or silicates. Dr. Washington refers to earlier theories of the interior of the

earth being an iron-nickel alloy, a theory based on the magnetic character of the earth, the nature of meteorites, the earth's high mean density or specific gravity, and the occurrence in places of native iron in basalt. This theory he accepts in part, but as nickel and iron (atomic weights 58.7 and 55.9) are lighter than the metallogenic elements in general, which range, in his diagram,[27] from copper (63.6) to uranium (238.2), and heavier than the petrogenic elements in general, as, for example, silicon (28.3), sodium (23); aluminum (27.1), and magnesium (24.4), he is moved to suggest (in which he follows certain earlier thinkers) that the nickel-iron is a zone, not a core; that it underlies the superficial silicate zone composed of igneous and other known rocks; and that the heavier metals underlie, the heaviest being closest to the center. This is an acceptance of the hypothesis of an onion-layered arrangement of the earth's structure according to specific gravity, such as was long ago postulated. Dr. Washington finds support for this theory in Abbot's views as to the distribution of elements in the sun. Abbot observed that the intensity of the spectra of the various elements arranged by natural groups, taken as a whole, diminishes with increase in the mean atomic weight of the group; and he reasons that "the decrease of intensities with increasing atomic weights seems to depend on the depth of these gases below the sun's surface."

I am inclined to accept the arrangement of substances according to atomic weights as more likely to obtain in the sun, where we have apparently some direct evidence tending in this direction, than in the earth, where I do not see that we have such direct evidence. The theory, as I understand it, postulates a symmetrical arrangement, beneath the silicate crust: in other words, a similar section along each radius, showing a like succession and proportion of elements. The distribution of metallographic provinces, as I have shown, indicates not homogeneity but heterogeneity;

[27] *Op. cit.*, p. 780.

and this is a direct or at least earth-derived line of evidence. There are other lines of direct evidence negativing the idea of a universal zone of nickel overlying zones of the heavier metals. The native iron in basalts in various regions is not to an important degree nickeliferous; therefore, the argument by analogy with meteorites is impaired. If other heavenly bodies have a layered arrangement of metals underlying a zone of nickel-iron, why are not the meteorites composed in part of these other metals? The metallic ones are evidently derived from the break-up of exclusively nickel-iron bodies, containing some silicates and carbon. Moreover, the known distribution of nickel on the face of the earth is phenomenally concentrated, the Sudbury, Canada, deposit containing most of the known nickel in the world, and the other chief deposit being located nearly at the antipodes, ten thousand miles away, in New Caledonia.

It is reasonably well demonstrated by the study of ore deposits and metallographic provinces that a nickel-rich layer does not everywhere directly underlie the siliceous crust, to be in turn underlain by the heavier metals. Reverting to the type province of Arizona, again, the stable deep substance whose existence is logically indicated is rich in copper but not in nickel. The atomic weight of nickel is 58.7, of copper 63.6. According to the onion-layer theory, metallic copper would indeed directly underlie metallic nickel, with metallic iron (55.9) and manganese (55) overlying the nickel, and metallic cobalt (59) associated with the nickel may occur intimately associated with copper, as rock magmas into the ore magmas, or at least out of the ore magmas into the ores, as sulphides, just as iron and copper are, to a large extent; and in nickeliferous provinces the nickel may occur intimately associated with copper, as at Sudbury. Therefore, if in Arizona there were nickel and cobalt overlying the copper of the deep stable zones, or even associated with the copper at its source, we should infallibly have had much of it in the Arizona ore deposits.[28]

[28] An exception to the complete absence of nickel and cobalt in Arizona

This suggests that perhaps between the incandescent stage of the earth that we seem to see exhibited in the sun, and the stage where all but the outer cover became fixed and rigid, an intermediate state of high fluidity existed; and the processes that then operated led to wide grouping of the elements, in ways that we cannot picture, into areas that we cannot explain; and, therefore, that the final result was not an equal composition along each radius, but a different composition for each, at least in its outer portion, and as far down as we can reason; and we have no other plain evidence. These processes seem to have terminated, largely at least, before the beginning of what we know as the geologic record. But it may well be that in spite of the present general stability of this inner earth, the gaseous and the lighter elements are still in some places and under some conditions rising as of old, to vivify and lend motive power to the magmas of the zone between the inner earth and the essentially rigid crust. It is, moreover, probable, if not certain, that the transition from the magma zone (actually or potentially fluid zone) to the underlying stable zone is a gradual one.

Since writing the above, I have found what appears to me to be a very remarkable piece of additional evidence bearing on these problems. I have received and studied the "World Atlas of Commercial Geology," published by the United States Geological Survey (Washington, 1921). On these maps the ore-bearing localities in the world are mapped separately, accurately, and quantitatively. With these maps in hand, let us take up again the distribution of silver in the Western Hemisphere, adding this new evidence to the discussion above. I have previously remarked on the relatively wide distribution of silver, as compared with its

is the Monte Cristo mine, near Wickenburg. Here we have unexpectedly an ore of the (Ontario) Cobalt type. As described by E. S. Bastin at the meeting of the Society of Economic Geologists in December, 1921, the ore is of considerable richness and contains native silver associated with cobalt and nickel arsenides. The ore is a replacement of pre-Cambrian granitic gneiss; at one point a basic dike is closely associated with it.

relative abundance in the earth's crust, but that it was most concentrated in that part of the peri-Pacific province which lies in North and South America. In these maps under discussion the quantitative basis brings the concentration of silver into a clearer symbolic representation. They are, to be sure, production charts, based on the production of the different districts for the year 1913; and so only partly suit our purposes. A chart showing total production to date is what we should have for this purpose. Let us take, however, Plate 42, showing the production of silver in North America for 1913. We perceive a very remarkable string of silver-producing camps in Mexico, separated each from the next by a hundred miles more or less, from the Arizona border to near Mexico City, a distance of about a thousand miles. These camps are famous and productive —Cananea, Dolores, Santa Eulalia, Parral, Mapimi, Velardeña, Concepcion del Oro (Mazapil), Charcas, Zacatecas, Guanajuato, Pachuca, and El Oro. These are all in a *straight line,* or a narrow straight zone; the extension of this line a little farther south—about 300 miles—runs through Oaxaca and so into the Pacific. Extending this same straight line to the northwest, it runs through Tonopah, in Nevada, and so, in Southern Oregon, into the Pacific. I have copied the chart, adding only the straight line which I describe, in Fig. 74.

Now if we turn to Plate 48 (Fig. 75), where the 1918 silver production of the United States is given in more detail, we find further evidence that this line or narrow northwest zone is indeed continuous between Mexico and Tonopah. The map shows, on this line, the districts of Cochise County, Pima County, Globe, Prescott, and San Francisco, in Arizona; and Clark County, in Nevada. Continuing the line northwest of Tonopah, it runs through Mineral County, the Comstock Lode, and the district of the Northern Sierras. Between these "high spots" thus mapped, there are, as is well known, many other camps which contain silver ores. There is thus aligned a very

remarkable string of silver deposits, including many renowned for their richness and production, lying in an almost

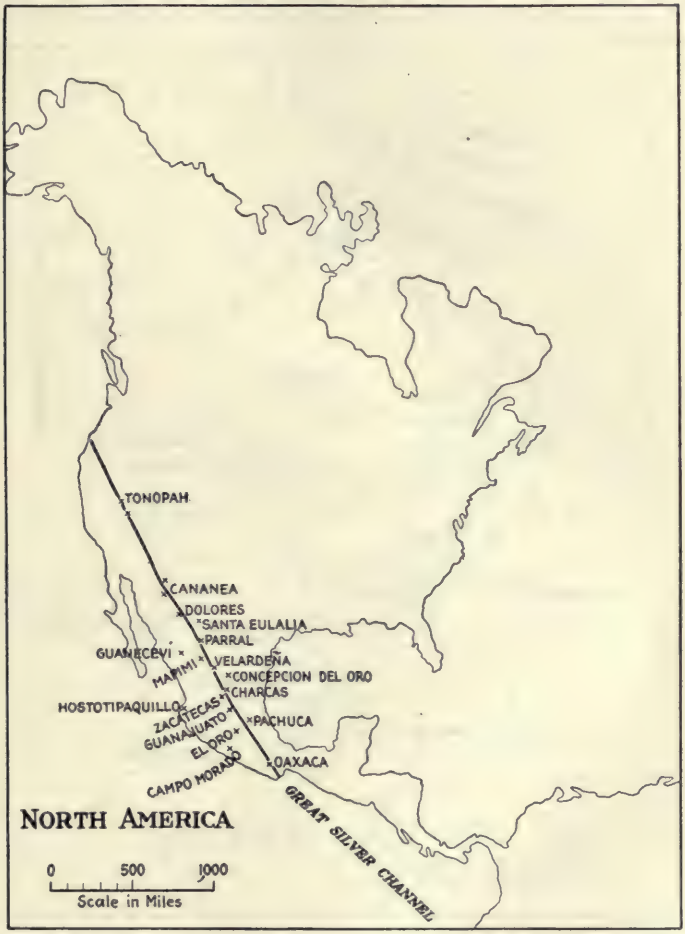


Fig. 74.—The Great Silver Channel in North America. Based on Plate 42, "World Atlas of Commercial Geology," U. S. Geol. Surv., Part I; Washington, 1921. The continuous line indicating the chain or channel, and the designation Great Silver Channel, are my own; also the recognition of this line.

perfectly straight line or narrow zone nearly 2,500 miles in length—a chord subtending the swelling arc of the Pacific Coast line of Mexico and California.

All this is remarkable enough, but if we extend this line straight southeast till it again strikes land in South America, we find that it strikes quite accurately and coincides

FIG. 75.—Principal silver camps of the Western United States. Based on Plate 48, "World Atlas of Commercial Geology," Part I., U. S. Geol. Surv., 1921. The crosses indicate the principal productive camps in 1918. The lines indicating ore belts or ore channels, and the recognition of the alignment into two systems, northeast and northwest, are my own.

with the great silver belt of Peru and Bolivia! This is indicated clearly on the world map (Plate 41), but is better proven in the map of South America (Plate 43), where the

line may be followed from the coast at the Zaruma district, through the districts of Hualgayoc, Cerro de Pasco, and

FIG. 76.—The Great Silver Channel, or Silver Belt, in South America. Based on Plate 43 of the "World Atlas of Commercial Geology," Part I, 1921. Crosses show principal silver-producing camps in 1913. The drawing of the lines indicating belts or channels of ore, and the designation of the Great Silver Channel, are my own.

Santa Lucia, in Peru, into Bolivia, where it passes through Potosi and other silver-bearing camps on this belt. The

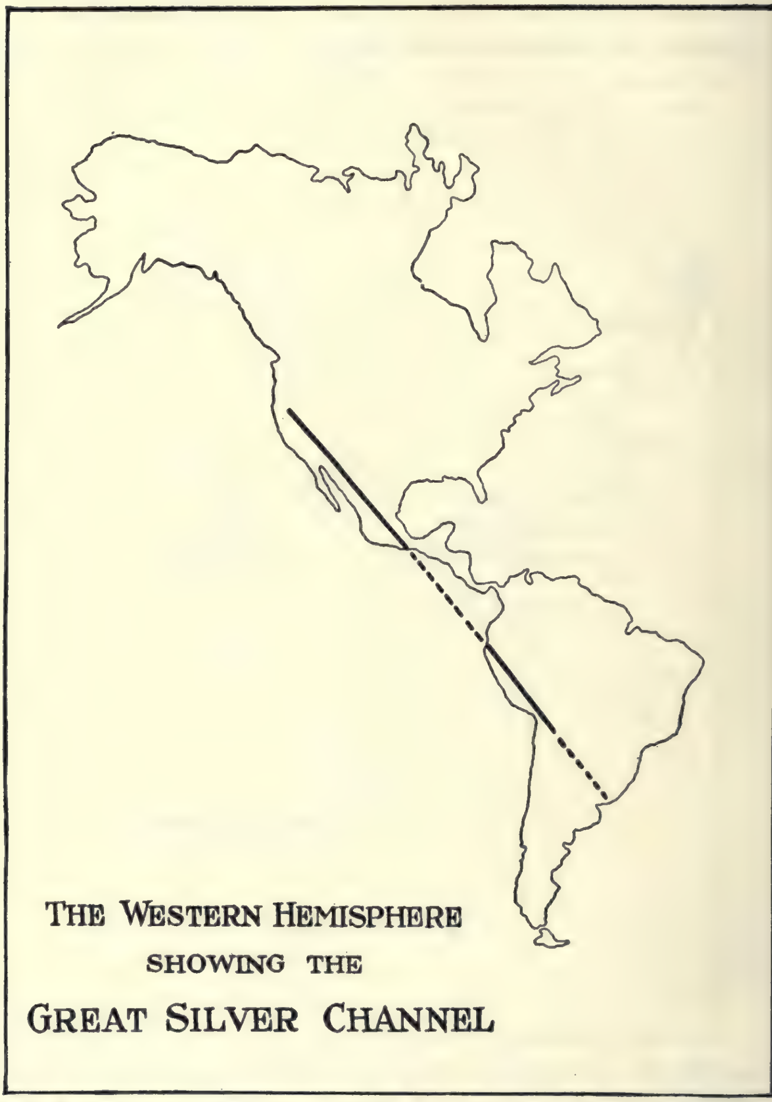


FIG. 77.—Based upon Figs. 74 and 76: showing the Great Silver Channel of the Western Hemisphere. See text.

total distance of this northwest-trending silver-bearing belt in Peru and Bolivia is some 1,600 miles, and there is no question as to the continuity of the belt. I have shown this in Fig. 76. Nor does there seem to be much question as to the identity and continuity of the North American line (above described) with this South American line, as is shown in Plate 41, a portion of which is reproduced herewith, on which I have drawn the silver belt in question, in North and in South America, and indicated the connection (Fig. 77). The total length of these two belts, and the connecting gap which lies in the Pacific, is about 6,000 miles, the connecting segment submerged in the Pacific being nearly two thousand miles long.

Along this line in North and South America occur most of the celebrated silver mines in the world, like the Comstock, Tonopah, Santa Eulalia, Guanajuato, Pachuca, Cerro de Pasco, and Potosi. This wonderful straight line slashes clean across mountain ranges and other geologic structures, and continues its course independent of them. This is shown in Nevada, where it cuts at an angle of nearly 45° across the trend of the north-south-trending desert ranges. In Mexico, it shows an utter disregard of the main geologic features and mountain chains—starting in northern Sonora west of the main range, or Sierra Madre, it cuts diagonally across this on to the central Mexican Plateau, with its short desert ranges; and in the south of Mexico, its unswerving course carries it back across the Sierra Madre again, for this range curves much like the west coast line. In Peru and Bolivia, it coincides with the general trend of the Andes. It is in the gap between Mexico and Peru, where its extension is assumed, that the most utter lack of any relation between it and the mountain chains of the crust is shown, for here it crosses the depths of the Pacific, and part of it runs where the ocean is 2,000 to 3,000 fathoms (12,000 to 18,000 feet) deep; while in South America, where it coincides with the Andes, it lies mainly in country more than 12,000 feet above sea level; and in Mexico and in the

United States it lies in a plateau country several thousand feet above the sea.

Not only does the straight course of this Great Silver Belt disregard geography, but it disregards geology as well. Tonopah and the Comstock, in Nevada, represent deposits of the later Tertiary. In Arizona, the silver camps on this line correspond with the copper camps, and vary accordingly in geologic age from pre-Cambrian through post-Jurassic to post-Cretaceous. In Mexico, most of the camps in the northern part of the country are probably immediately post-Cretaceous, those in the southern part middle to late Tertiary. In Peru and Bolivia, the deposits are partly Tertiary, partly perhaps older. Therefore, the same conclusions are indicated as were deduced above for the copper deposits of Arizona—that this silver belt is very ancient and stable, and has manifested itself at any geologic period when igneous activity along this belt has furnished the necessary excitant and means. Indeed, in Arizona, the silver belt coincides in general with the belt of maximum copper deposition.

In this marvelously straight and persistent Great Silver Belt we have a striking symbol which we may decipher if we can. It is not at all, as manifested in the visible rocks, a fissure or a fissure system. The veins in the districts mentioned have their own courses and systems. At Tonopah, for example, they run east-and-west; at El Oro (in Mexico) they run northwest; at Asientos northeast, at Charcas nearly east-and-west; at Santa Eulalia mainly north-south; and so forth. It is not a mountain-making structure, a fault or a fold zone: as noted above, it cuts across all minor and major structural features without paying any attention to them. In what then does it consist? Its persistence, definition, and great length tempts us to classify it vaguely, gropingly, as a structural fracture, but it is an invisible one, disregarding and underlying all known rock structures, mountain chains, and lines of igneous intrusion. Here we have a striking supporting proof of our

conclusions reached in considering the Arizona copper province: that this metallographic province means a stable highly copper-bearing substance in depth, not only far below the crust but below the unstable magma zone as well. Here, in this narrow metallographic province or ribbon which I have called the Great Silver Belt or Channel, is a Structural Feature which plainly underlies the wrinkles of the crust, with all its faults and folds, great and small—even such faults of semi-continental scale as the fault which bounds the Sierra Nevada (and probably the Cascades) on the east, and blocks out these great ranges; it underlies the effect of the loftiest mountain chains, and the magma reservoirs beneath them. We may conceive of it as a Structure; but it is a structure of geometric simplicity such as we do not have in the crust. We perceive here dimly a symbol defining to some extent a peculiar and simple framework or arrangement of the heterogeneity of the under-earth. We may perhaps interpret it as a belt along which—in that period which precedes all recognized geologic history, when the elements migrated freely in the fluid earth, to achieve the heterogeneous distribution which is indicated by the phenomena of metallographic provinces—silver notably was concentrated and segregated. We naturally picture such a straight line of segregation as a rift or fissure in the cooling globe, at a depth untouched by the subsequent flowage and adjustments of the solid or fluid outer zones; and thus we are led to set up as a trial hypothesis the formation of the heterogeneity of the stable under-earth as aided by regular fissuring. There presents itself to my mind at present at least one other trial hypothesis, which also postulates deep and regular globe-fissuring, but does not necessarily link up this fissuring with the period of origin of globe-heterogeneity. Rather it pictures the grand fissure systems as perhaps later, and that along them the stable highly metallic under-earth has bulged up in geometrically regular ridges above the normal deep zone; and that the magma tides in

the overlying unstable magma zone became specially metalliferous by flowing against and over these long reefs. Such an alternative trial hypothesis, which I think I favor over the first, would still, I repeat, postulate globe-fissuring, and still assign an immensely remote geologically prehistoric period for the fissuring; but it would nevertheless contemplate a possible immense lapse of time between the globe-fissuring and the earlier origin of globe-heterogeneity.

Silver is not the only metal that characterizes and makes notable the Great Belt, although it is the most persistent one. In Nevada, and also in Peru, as well as in some districts in Southern Mexico, gold occurs associated with the silver; copper is abundant in Arizona, Mexico, and Peru; and tin in Bolivia. Even molybdenum is associated in Arizona and Peru. But it is silver which is the essential and conspicuous metal of the whole zone. Here we see indicated a certain superposition or conjunction of one metal on another. The peculiarity of the tin ores of Bolivia, for example, unique in the world, of occurring in association with rich silver ores, is seen to be due to a local (in Bolivia) conjunction of tin with this segment of the Great Silver Belt. The copper which in so many places is characteristic of this belt is not, however, always evident, nor does its distribution always follow closely that of the silver. Although in Arizona, as above stated, the zone of maximum copper production roughly coincides with this Great Silver Belt, and although the same is largely true in Peru, yet the remarkably rich copper belt of Chile has a different trend and extent, running due south from its junction with the Great Silver Belt in Bolivia. Comparison of Plates 35 and 43 of the Atlas above mentioned shows that the principal silver deposits do not extend down along the Chile Copper Belt, from the junction, as far as the principal copper deposits, while the gold deposits extend the whole length of this Copper Belt, and further, to Cape Horn. The tin of Bolivia (and perhaps also the antimony) may be said to occur at the intersection of the northwest

Great Silver Belt with the north-south Chile Copper Belt. The atomic weights of silver (107.9) and tin (118.7) are close together, and silver occurs in Bolivia above the tin; but no theory of the arrangement of the under-earth according to specific gravity can explain why this conjunction of silver and tin occurs strikingly in only this one spot on the globe; while the conjunction of gold (197.2) and silver (107.9) is very common; and also the conjunction of copper (63.6) and gold, as along the Chile Copper Zone. We are forced back to the hypothesis of a heterogeneous highly metallic stable under-earth, underlying the magma zone, whose heterogeneity was the result of some vast primeval process of chemical segregation in a fluid and cooling earth, in the latter stages of which fissures developed.

If the Great Silver Belt indeed represents a sometime fissure zone of the cooling under-earth, it is to be noted that its straight course indicates verticality, or a radial cracking. Note that the Silver Belt coincides with the Andes uplift in Peru and Bolivia; and while it does not coincide with any uplift in Mexico and the United States, yet in North America the main ranges and the coast line have a general, although irregularly, quite similar trend. We perceive, therefore, the probability that the continents are built up, in some way, on the basis of cleaner and straighter intersecting geometrical patterns of the under-earth; and what these patterns are, we apparently can elucidate only from the study of ore deposits. If we were able to plot them more completely they might resemble the canals of Mars. But that the continents are in part bounded by approximately straight lines has long been recognized; and this is specially marked in the case of South America, and to a less degree, North America. One of the very longest lines delineating the continents is that northwest line which runs along the west coast of North America, and, after interruption, appears to be continued in South America; and this parallels or follows roughly the Great Silver Belt, as above explained. Therefore, the Silver Belt

under-earth fissure was perhaps that along which the North American continental area (on the west side) originally broke away from the ocean area, on account of the less average specific gravity which this block had acquired in the distribution of heterogeneity, in the stage which has been postulated; and accordingly other approximately straight outlines of the continents or of some of the grander features within the continents may be represented by straight under-earth fissures. The actually irregular (in detail) coast lines may be conceived of as representing a sort of later upholstering of these geometrical blocks, by the flowing of the magma layer against and beneath them, to restore the isostatic balance which had become affected by erosion and to relieve the telluric pressure of the relatively superficial suboceanic fluid magma layer; and they also represent many other factors. By such flowage, and the piling up of mountains (by magma additions, by compression, or by faulting), a line formed by several fissures which have different directions, but which are intersecting, may be covered by a single mountain chain, as in the case of the Andes of the west coast of South America, which passes from the north-south trend of the Chile Copper Belt to the northwest trend of the Great Silver Belt, and thence to a northeast trend which I will not here attempt to analyze with respect to its under-earth fissure and its metallic characteristics. Another case among many is that of the lofty Alaskan range in Alaska, which makes a right-angled turn, passing from a northwest to a southwest course.

Are there other under-earth fissure-like metallographic belts which we may observe? I believe that study will expose a number. In Colorado, I described in 1908 the mineral belt which runs northeast across the state, cutting diagonally across a series of bold mountain uplifts, from the high east face of the Rocky Mountains near Boulder to the complicated dome-like uplifts of the San Juan, a distance of several hundred miles.

The ores in this belt are somewhat complex, but the most

characteristic metal is silver, and next gold, so that the belt is shown on the same sheet of the United States Geological Survey Atlas as that from which I have described the Great Silver Channel. The map of the United States (Plate 48) shows the Colorado belt of gold and silver, running almost exactly at right angles to the Great Silver Channel in Arizona and Nevada (Fig. 75). This Colorado Channel, if I may so call it, differs metallographically from the Great Silver Channel in being relatively poor in copper, in which the Great Silver Channel in the United States is rich; and in being relatively rich in lead and zinc, in which the Great Silver Channel is much poorer. Only a small amount of copper, occurring with the gold in the pyritic ores, as, for example, in certain mines in Clear Creek County, Colorado, marks the transition stage from the auriferous pyrite zone down to the copper zone; nevertheless, we have in Boulder County the apparently anomalous development of important tungsten ores, representing a zone below the copper zone.

The existence of this belt for nearly a hundred miles, from Boulder to Leadville, is put beyond debate by its continuity. And in this indubitable section it shows its strange peculiarity of cutting obliquely across the ranges, and across the dominant sharp folding in that portion where the sedimentary rocks exist. These ranges, and the axes of the principal folds, trend a little west of north. What type of structure, then, is this mineral belt which pursues its way regardless of the great folds into which the rocks have been wrinkled? We are bound to consider it as essentially underlying and independent. It is a belt which has been selected for intrusion, not only by mineral veins, but also by igneous dikes, of various kinds, representing siliceous to intermediate magmas. The chief igneous intrusions of this northeast belt represent variations of a monzonitic magma, just as the igneous intrusions and extrusions along the path of the Great Silver Channel in

Nevada, Arizona, Mexico, and Peru represent variations of a monzonitic magma.

As shown on the map,[29] the San Juan district in Southwestern Colorado lies exactly in the line of this northwest-trending Boulder-Leadville belt, and is characterized petrographically by similar monzonitic igneous rocks, and metallographically by similar silver, lead, and gold ores. It seems to be an extension of the belt. This is further shown by the intervening mining districts shown on the map, and especially the mineral belt in which Aspen lies, which trends like the main belt and is in a larger way a part of it, and itself cuts across the great folds and other major geologic structures. Moreover, the central and richest part of the San Juan ores, from Lake City to Rico, runs northeast, showing its nature as a portion of the Colorado Channel.

The fact that between Leadville and the San Juan, and from the San Juan southwest, in which stretches the veins and dikes are not found, the highly folded strata and the mountain ranges show no indication of this belt, proves anew the underlying nature of the striking and continuous structure thus shown. It is only, it will be remarked, in the pre-Cambrian crystalline rocks, in the northeast 100 miles or so of the belt, that the dikes and veins, cutting diagonally across the mountain uplifts, demonstrate in detail the identity and continuity of the Structure. Further southwest, where the sedimentary rocks, from the Cambrian to the Tertiary, cover up the crystalline basement, neither the igneous rocks nor the veins have reached up into the rocks now exposed by erosion, except in certain places; and these overlying rocks in such intervening areas contain then no continuous trace of the underlying northeast belt which I call here the Colorado Channel (Fig. 78).

In my original study of this belt,[30] I pointed out that it was a belt of persistent and continued northeast and

[29] J. E. Spurr and G. H. Garrey, *Professional Paper* 63, U. S. Geol. Surv., Plate XVIII.

[30] *Professional Paper* 63, U. S. Geol. Surv., 1908, p. 118.

southwest fissuring, as shown by the trend of dikes, veins, and faults; and that this was a zone which had afforded repeatedly relief of strain from the forces acting in an east-west direction, which had crumpled the rocks into north-south folds. Never thoroughly satisfied with this as an

Fig. 78.—Tertiary ore deposits of Colorado-New Mexico. Adapted from Plate XVIII, Professional Paper 63, U. S. Geol. Surv. (Spurr and Garrey), and Figs. 1 and 2, Professional Paper 68, U. S. Geol. Surv. (Lindgren and Graton). Note two distinct northeasterly belts or ore channels, the Colorado one northeast, the New Mexico one north-northeast.

ultimate explanation, I am now impelled to discard it. The facts as to the repeated forming of fissures along lines which were very early determined are unquestionable; but quantitatively the amount of movement seems insufficient to explain the phenomenon of the belt. In the pre-Cambrian

crystallines, where the nature of the manifestations involved is reduced to the simplest terms, the amount of movement and faulting before the intrusion of the dikes and veins appears very small, usually perhaps not more than a few feet. The fault movements later than the dikes and veins are the chief ones, but even these are small; the largest was observed in the Georgetown-Idaho Springs area, being a horizontal faulting of a dike amounting to almost 200 feet. In the other sections of the belt, where it lies in the post-Archæan sedimentary rocks, these measure more clearly the amount of disturbance. A great deal more movement is shown, both in folding, and in some very heavy faulting; but, as discussed in an earlier chapter, the main faulting, as is characteristically the case with ore deposits, has been subsequent to the intrusion of the igneous rock and the ore deposition, and may with some confidence be ascribed to adjustments of the underlying intruded magma. In other words, the pre-intrusion fissuring and faulting, which can be appealed to for the localization of this zone of dikes and mineral veins, seems quantitatively inadequate as a cause.

In this belt, in the Sawatch range opposite Leadville, is the Mount Champion gold mine, which I have mentioned in Chapter IV, p. 193, as consequent upon a pre-Cambrian domelike intrusion of granite. Does this mean that the metallographic belt which I have called the Colorado Channel existed before the post-Cretaceous revolution, folding, uplift, magma intrusion, and ore deposition? Recently, what appear to be the greatest molybdenite deposits in the world have been discovered at Climax, well within this belt, between Breckenridge and Leadville. According to Mr. F. L. Hess, these deposits are probably Tertiary. Considerable molybdenite which I have seen from the vicinity of Breckenbridge (near Climax) occurs as an essential constituent of pegmatite (see p. 80) and is probably pre-Cambrian. The possibility that this metallographic belt or channel has been stable throughout all geologic time as we reckon it, therefore presents itself. Although there is little

molybdenite in the other Tertiary ores in general, there is considerable in those of Boulder County. Such evidence is, of course, far from being as convincing as the permanency of the notable copper deposition at all critical geologic stages in the Arizona province, but is suggestive of the same conclusions. The thought then comes that it is on account of the deep position of the Colorado Belt magma channel, below the crust, that the belt is metal-

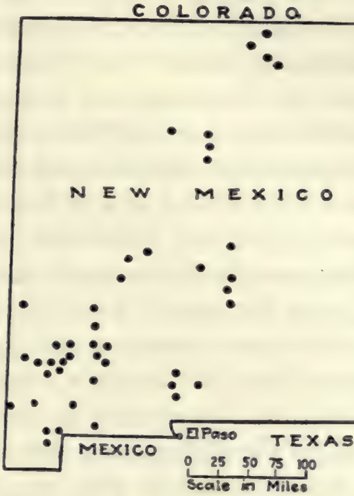


FIG. 79.—Tertiary ore deposits of New Mexico. Adapted from Lindgren and Graton: "Ore Deposits of New Mexico," Professional Paper 68, U. S. Geol. Surv., Figs. 1 and 2, p. 52 and p. 68. Note definite northeasterly belt of ore deposition.

liferous, for the reason that this magma belt has touched and been enriched by the still deeper, stable, and permanent zone rich in the metals, a zone which underlies the magma zone. There are plenty of igneous rocks in other parts of Colorado which are not accompanied by ore deposition.

New Mexico shows a north-northeast Tertiary ore belt, trending obliquely across the mountain ranges. This is shown in Fig. 79, where the individual camps are designated; in Fig. 78, however, the various occurrences are

grouped into general mineralized areas, as has been done for Colorado. It will be noticed that the figure shows the north-northeast New Mexico ore belt swinging more to the north, and also diminishing in importance; and so it seems to tie up to certain important districts in Colorado which are outside the general Colorado ore belt—districts like Cripple Creek and the Rosita Hills. And the Colorado and New Mexico belts would appear to have a confluence in Northern Colorado (Boulder and Gilpin counties).

Studying the Geological Survey Commercial Geology Atlas (Plate 42) again, let me now refer to the Alaska Gold Belt, which is shown on this map as a straight northwest-trending (west-northwest) line between Nome and the Klondike, and taking in the principal gold-mining districts. This gold belt is pre-eminently a placer belt (the lodes are usually insignificant); and the importance of the placers depends on the fact that Alaska escaped the glaciation of the Glacial period, and the placers have, therefore, had an immense time for the concentration of the gold. This perhaps explains why the gold belt has not been economically conspicuous past the point where on the east it passes into the glaciated region, in the Pelly River area. In its known course northwest from the Pelly past the Klondike and other Yukon and Tanana gold districts to Nome, it traverses rocks of different types. In part of the region, as in the Birch Creek district and parts of the Forty-Mile district, it lies in the crystalline, probably pre-Cambrian (Proterozoic) sedimentary schists. These are intruded by a granitic magma, showing various differentiation types, and one of these extreme types consists of auriferous quartz veins. A later set of veins and dikes intersects the overlying Paleozoic rocks. There were repeated periods of intrusion and possible gold-vein deposition, up to as late as post-Cretaceous but pre-Eocene. The different periods of intrusion and mineralization are not firmly established, and I am inclined to consider the principal period as pre-Cambrian, although other geologists differ with me in this. The

difference, however, does not affect the question I am discussing.

This straight gold-bearing belt cuts sheer across the lines of folding, the various geological formations, and the mountain uplifts, which run northwest in the southern and eastern part of Alaska, and turn at right angles and run southwest in the northern and western part, as is indicated by the two elements of the southern coast line of Alaska, trending at right angles to each other.

At the western end of this Yukon mineral belt in the Seward Peninsula, near Nome, the principal tin deposits of North America are found. They occur in connection with the intrusion of granite into Carboniferous (Mississippian) limestones, and are, therefore, post-Mississippian.

Again, on the Geological Survey Commercial Map of the United States (Plate 48) there appears to be a northeast zone of silver production in Montana and Idaho, altogether parallel with that in Colorado, running through Neihart and Butte, in Montana, into Custer County, in Idaho, and about 300 miles in length (Fig. 75). As a gold belt this extends further at either end, so that altogether it runs (as a well-marked silver-gold belt) from the Little Rockies district in Montana to the Boise district in Idaho, a total distance of 500 miles. This striking belt cuts at right angles across the main ranges of the Rocky Mountains and their subordinate ridges, but is marked in part by isolated domical uplifts, such as that of the Little Rockies.

Also, there is a northwest belt of production of silver and some gold (Fig. 75) which runs from the centre of the northeast belt just described, near Butte, through the famous Coeur d'Alene district, to the Republic-Rossland districts on the border between Washington and British Columbia. This trends obliquely across the Rocky Mountain ranges. At the intersection of these two belts is the great copper camp of Butte.

In Utah, Butler[31] has recognized the fact that the known

[31] *Professional Paper* 111, U. S. Geol. Surv., 1920, p. 88.

igneous rocks, both intrusive and extrusive, are arranged in rather definite though discontinuous zones which have a nearly east-west (east-northeast) direction (Fig. 80). The largest of these zones lies in the southern part of the state, and extends clear across it to Nevada. The second main zone extends from the western end of the Uintah Mountains (which is an east-west uplift probably due to a surgence of magma in depth)[32] westward. The Uintah Uplift continues this line clear across Utah, and it also crosses the state into Nevada. Butler's map (Fig. 80) also shows a minor zone in the northwestern part of the state, apparently aligned in a direction a little north of east. Butler draws no theoretical inferences from this alignment, but combined with his description of the structural history, I see the likelihood of a connection between the two.

The great period of deformation of the rocks—of folding and faulting—in Utah, occurred, according to Butler, at the end of the Mesozoic (Cretaceous) or early in the Cenozoic (Tertiary), when there was "a general uplift accompanied by folding, by overthrust and other faulting, by igneous intrusion, and by doming which was at least in part the result of intrusion." "The period of upheaval and intrusion was overlapped or followed by one of volcanism, during which immense quantities of lava and tuff were erupted." The folds and the overthrust faults which occurred at this period run in general north and south, or nearly at right angles to the zones of igneous intrusion and uplift. "The folding and overthrust faulting is greatest in a north-south zone which extends across the state and passes through the Wasatch Mountains." The author notes that in the northern continuation of this belt in Southeastern Idaho and Southwestern Wyoming "the folds are close, in many places overturned, and are associated with extensive thrust faulting." This folding and faulting, the author states, are doubtless contemporaneous, and "resulted from forces tending to compress the area in an east-west

[32] See p. 216; also Butler, p. 601.

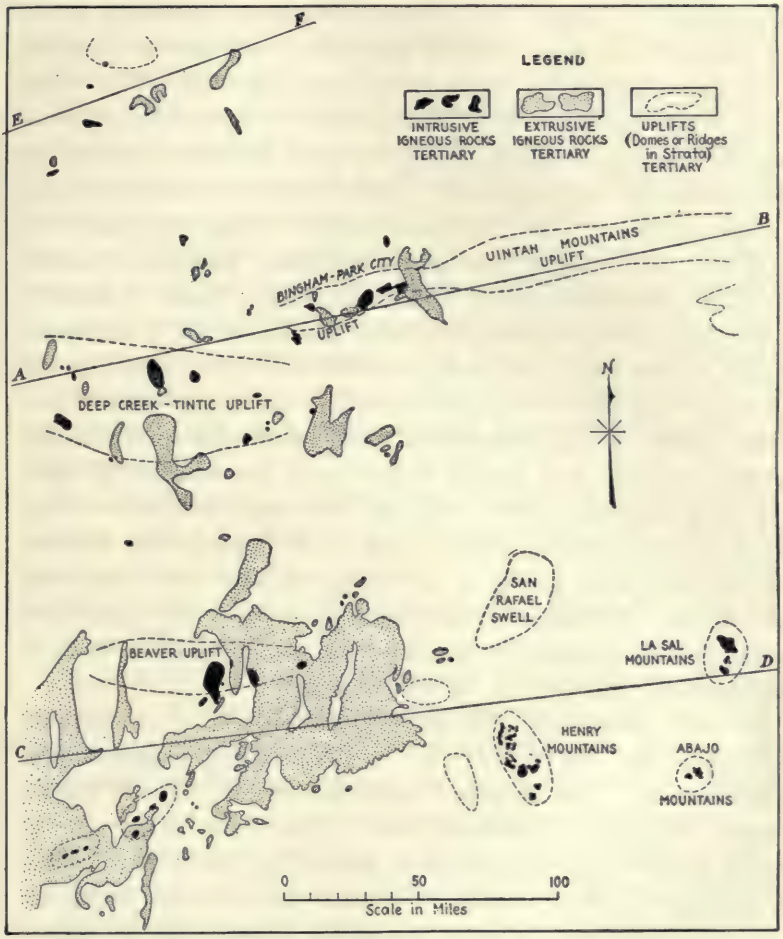


FIG. 80.—Partial geological map of Utah, showing Tertiary intrusions and uplifts. Copied from Butler: Professional Paper 111, U. S. Geol. Surv., Plates IV and XI. I have added the lines A—B, C—D, and E—F, which I designate as follows: A—B, approximate central line of mid-Utah magma stream and main belt of Utah ore deposition. C—D, corresponding line for south Utah magma stream. E—F, probably another magma stream; not sufficiently shown. These data support (a) the east-west course of magma streams; (b) the origin of domes by magma surgence.

direction."[33] These overthrown folds and faults dip flatly to the west (p. 217), whence the author concludes (p. 103) that the compressing force came from the west. What was this compressing force? The author follows the current theory which postulates thrust from the Pacific basin due to accumulating sedimentation; but to me the essential contemporaneity of the east-west lines of igneous intrusion and the north-south lines of compression suggests strongly a causal relation—namely, that subcrustal streams of molten rock, flowing from under the ocean basins (p. 232), gathered more or less into channels parallel with the direction of flow, or east and west; and that it was the powerful forward creep of this subcrustal fluid which compressed the overlying crust and locally shortened it by overthrust folding and faulting. Not only do the north-south trending axes of compression seem to me to be apparently related to the east-west zones of contemporaneous intrusion, but the existence of these zones tends to support the theory of subcrustal fluid creep from under the ocean basins to restore unbalanced isostasy to the continents.

Indeed, although the generalizations of this volume (Professional Paper 111, U. S. Geol. Surv.) ignore this explanation, the detailed description of the Wasatch range, and the inferences drawn therefrom, argue for it most strenuously. It is here stated (p. 301) that "The injection of great bodies of diorite and diorite porphyry into the sedimentary rocks obviously caused intense deformation" and that the compressive force was very great.

"The invasion of the Carboniferous formations by diorite porphyry magma, apparently forcing its way irregularly north-eastward, would seem to have been accomplished under very high pressure. Deformation directly traceable to it is seen in several places." Details in the Silver King mine, showing crushing and compression, are given, and it is added that "the great intrusive bodies may reasonably be supposed to have acted in precisely the same manner

[33] *Op. cit.*, p. 102.

on a proportionately large scale"; and specifically the formation of certain great overthrust faults is thereby explained (see p. 214).

"The evidence indicates that a series of intrusive bodies extends in a narrow east-west belt across the Wasatch range; that they invaded the Park City area from the west, breaking upward and eastward; that those in this area are thus the highest and easternmost members; that at the east end and ahead of this chain of intrusives the formations are thrust eastward, one formation completely over the next two normally overlying ones; and that directly in the path of the intrusives the formations have given way, chiefly on two great faults, and have moved relatively eastward at least two miles."

The existence of east-west channels or streams of fluid magma seems to explain the general east-west trend of veins in this western country. I have propounded the problem in the *Engineering and Mining Journal* of Feb. 28, 1920, as follows:

"Is it true that important mineral veins of the fissure type in western North America tend distinctly to strike easterly-westerly rather than northerly-southerly? It is so in my experience, and I have never seen attention called to what must, if true, denote some broad underlying principle. I mean this as a generalization, not an approximately exact mathematical statement. If the strike tendency is true as a generalization, why is it so in a region where the principal folds, intrusions, and faults follow a general northerly-southerly trend?"

No explanation was forthcoming. This Utah region is no exception to the law stated, for while the ranges and the major structures run north and south, the veins trend rather easterly and westerly. I have roughly tabulated and averaged the strikes given by Butler for the fissure veins of the Wasatch and find an average of N. 55° E., which is not far from the trend of the intrusive belt above described, which runs east-northeasterly.

The origin of vein-forming fissures has become rather clear to me, as a result of the study and comparison of many instances, and I have discussed it in Chapter VIII, and I will again take up the problem in a succeeding chapter. They are usually of slight displacement and represent the first fissuring of the rocks, subsequent to the intrusion of the local magma with which so many ore deposits are connected. Subsequent movement usually produces more profound faulting, which takes place leisurely, and is usually unmineralized. It is probable, as I have pointed out, that all this faulting, including the initial slight fissures, is mainly due to adjustments of the crust after magma migration (intrusion or extrusion); and plainly the first rifts permit the pent-up magma solutions to penetrate along them and form veins; whereas the later fissures are usually subsequent to the critical period when magma-ore solutions are available for intrusion. Vein injection is as definite an event as dike intrusion. The first fissures, according to this, would seem to predominantly (although not invariably) follow the trend of the causal magma body (see Chapter XVI, p. 725); and if the latter were more easterly and westerly in shape than northerly and southerly, the veins would conform.

If this relation is true, the inferences from it may be used in reverse form, and the general trend of mineral veins be used to denote the general trend and direction of flowage of the associated magma. For example, as the predominant east-west system of veins obtains in Nevada and Idaho, underlying streams (ridges) of magma moving along a general east-west direction before and during the period of mineralization may be inferred.

The main period of magma migration under discussion in Utah, which was post-Cretaceous, corresponds with that in Colorado, as does the general character of the magma.

Now, as regards mining districts, the map of Utah made by Butler and associates (Plate I) shows a very striking and practically continuous east-northeast belt of over 20

distinct mining districts in the southwestern part of the state, of which the principal producer has been Frisco (San Francisco). The length of this evident belt in Utah is about 150 miles, the width around 20 miles. Extended westward into Nevada, it takes in the important old camp of Pioche (Fig. 81). This belt cuts clean across the ranges of Utah and Nevada, which are north-south narrow ranges

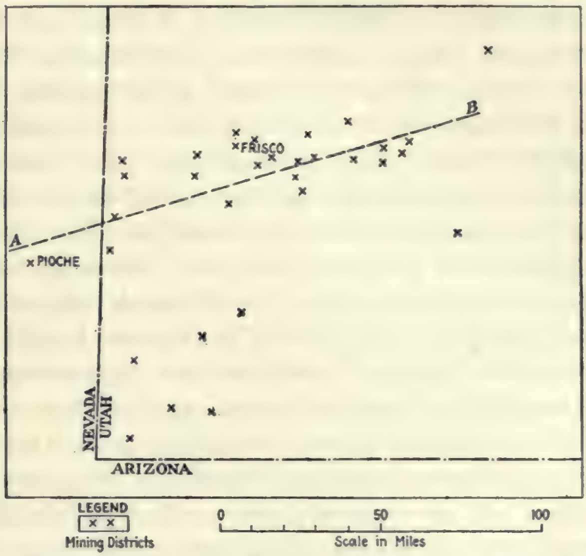


FIG. 81.—Mining districts of southwestern Utah; from Butler: Professional Paper 111, U. S. Geol. Surv., Plate I. I have added only the location of Pioche, in Nevada; also the line A—B, which appears to be the central line of an east-northeast ore belt, which lies within the zone C—D of Fig. 80. The mountains and ranges traversed by this belt run in general north and south.

separated by flat desert valleys; it coincides with the trend of the intrusive rock belt (C—D, Fig. 80), but the chain of ore deposits is more marked than the outcropping igneous belt. There is a parallel east-northeast belt of mining districts in the southwestern corner of Utah. Similarly, the belt of intrusives in the major Utah east-west zone—that in which lie Park City, Bingham, and Tintic (A—B, Fig. 80)—is marked on its westward course (it runs about parallel—

east-northeast—with the two belts just described) by many mining districts, from the Wasatch region west to the Deep Creek Mountains near the Nevada line, a distance of about 150 miles. It would require a map of the mining districts of Nevada, such as I have not made, to determine the extension of these Utah east-west magma-and-ore belts into Nevada, but as to this Bingham-Deep Creek belt, its extension westward would seem likely, and would include the notable ore deposits of Ely, Hamilton, Eureka, and Austin.

Ore deposits extend along the north-south Wasatch range in Utah for 150 miles or more; and, therefore, might easily be believed to have some relation to this bold north-south uplift. The evidence of these east-west (east-northeast) belts of intrusion and ore deposition shows that the relation of ore deposits to the north-south uplifts is illusory. The Bingham-Park City belt of uplift, intrusion, and ore deposition cuts square across the Wasatch range, and is continued by the Uintah uplift to the eastern border of the state, where the igneous rocks and ore deposits are submerged beneath the superficial crust; and on the west, with a slight offset, this general trend of uplift, igneous intrusion, and ore deposition runs through Tintic and Deep Creek into Nevada and thence westward an undetermined distance. The general strike of the veins (east-northeast) in the whole Wasatch suggests that they are all referable to this east-west magma flow.

The ore deposits of these Utah belts are large silver producers, and, therefore, these belts also may be distinguished on the Geological Survey Commercial Geology Chart (Plate 48). They also carry lead and gold, and locally copper. In respect to copper, the main Utah Ore Channel above referred to would apparently tie together Bingham and Ely (the Utah Copper and Nevada Consolidated mines).

These east-northeast Utah belts or magma-and-ore channels, like the Colorado Channel and others, pay apparently no attention to the lines of folding, faulting, and uplift of

the crust. This is well shown in Butler's map. In general, the magma-and-ore channels in Utah are at right angles to the main structures in the rocks, as the Colorado Channel is diagonal (at about 45°) to the main structures, while the Great Silver Channel of North and South America is in general parallel, and at the same time altogether indifferent to the local mountain structures. In all these cases the ore belts are on the whole more distinctive than the associated magma belts, and we shall have to reflect on these channels as to their dual nature.

The data which I have above outlined are, of course, sketchy, but do indicate the existence in North America of two sets of intersecting straight belts or channels of silver (with other metals), running respectively northeast and northwest. These channels correspond rudely in trend to the skeletal geometrical framework of the continent; and the major channel, which is of world proportions, parallels rudely the eastern side of the Pacific. Throughout the Cordilleran states—Colorado, Utah, Nevada, Idaho, and Montana—marked but less-marked similar channels run, at right angles to the master channel. It reminds one of a great irrigation ditch, with laterals at right angles. Apparently these described belts account for most of the great wealth of ore—especially silver, lead, and gold, as well as some other metals—in the Cordilleran region of the United States east of California, one of the richest metallographic regions in the world in these metals.

Here, then, is a discovery of prime scientific and commercial importance. This channel system is marked by a continuity or rather a chain system (like beads on a wire) of consanguineous magma occurrences and also consanguineous ore occurrences. In part—in large part—both magma and ore chains have no evident relation to the major belts of folding and faulting of the rocks, and therefore appear to belong to a zone below the zone of surface wrinkling and breaking. In part, however, in Utah and perhaps in Montana, the right-angled relation of magma-and-ore channels

to the chief lines of folding and faulting and the mountain uplifts and the local plain buckling-back effect, on the strata, of portions of the magma, where noted as intrusive into sedimentary rocks, indicates that the folding and faulting of the Cordilleran region, and the formation of mountain ridges, has been indeed probably due to a general magma flow or undertow, from the direction of the Pacific; and this explanation also will account for some of the astonishing flat over-thrust faulting found in certain parts of this region. The rocks of certain portions of the Cordilleran crust, according to this, are riding on the back, as it were, of a north-eastward- to eastward-moving magma undertow, and a strong horizontal movement is thus set up.

In Colorado the north-south mountain uplifts, the easterly continuation of the Utah system, indicate a continued eastern drag, beneath Colorado, of the same magma zone as that in Utah, where, as indicated by the intrusive phenomena along the Deep Springs-Bingham-Uintah general east-west belt of uplift, the magma becomes submerged in the eastern end of the state. Beneath such an eastward- and upward-moving magma in Colorado we must conceive, according to our theory, of the Colorado Ore Channel, which enriched the overlying magma and afterward was registered upon the rigid crust as a belt of depth-derived ore deposits and accompanying and related magma intrusions.

There may be, therefore, two distinct factors in determining these ore belts: the frequently straight-line, geometrical metal zones or ridges of the stable under-earth which are the fundamental bases for the major ore channels at least; and the flow inward to the continents, and from the ocean basins, of the magma which lies below the crust and above the stable under-earth, and which becomes markedly metalliferous in contact with these metal-bearing zones or ridges in depth. Such a metal-rich magma may rise up directly and will then coincide, as to position, with the ore channel of the under-earth directly beneath; or, carrying its metallic excess, it may stream on and may establish.

in the crust above, an ore zone following the course of the magma stream, which will have all the characteristics of and will be distinguished with difficulty, if at all, from the ore channels which are directly superimposed on the zone of metal wealth in the ultimate depths.

I believe that much can be accomplished in further elucidating this subject: 1, by separate mapping of the intrusive rocks of the world; 2, by careful *quantitative* mapping of the ore deposits of the world. In this latter mapping total production is the safest standard to work on.

I will call attention, in closing this chapter, to what may be another North American ore channel, which I have not closely investigated. The Geological Survey maps of the United States (in the Commercial Geology Atlas to which I have above referred) shows (Plate 48) the gold belt that runs from North Carolina to Alabama as parallel with the Colorado Ore Channel, and trending somewhat more northeasterly than the ridges of the Appalachians, which it, therefore, cuts across obliquely; and just northwest of it there is shown a parallel copper-lead-zinc belt (in which lies Ducktown). The distinction metallographically between the two belts may be due to relative depth of erosion, the eastern belt representing a deeper zone of deposition than the western. These belts are each three or four hundred miles long, and are well marked; it seems likely that together they may constitute an ore channel, as above defined.

CHAPTER XI

The Ore-Depositing Fluids Other Than Ore Magmas

This chapter deals with the element-concentrating or ore-depositing fluids other than the typical ore magmas. The ocean produces important deposits, thrown down from solution, especially by organic life. Landlocked waters throw down deposits in the same way, or by direct evaporation. Atmospheric waters, dissolving some elements, and leaving others, produce important residual deposits on land. Also, surface waters act mechanically to concentrate elements, such as gold and silica. But surface waters probably accomplish little concentration below the zone of active chemical reactions between the atmosphere and the rocks.

Hot springs are probably in part of magmatic origin, and are allied to the fumaroles of volcanoes. Neither hot springs nor fumaroles form at the surface any commercial accumulations of metals, but both do deposit small amounts of them, in some instances only. However, they must be distinct from the typical ore magmas, which have deposited so large a proportion of the primary metalliferous deposits.

Descending surface waters are very potent in enriching primary deposits at and near the surface, especially ores of copper; ascending hot waters probably also have some re-working effect. These hot-spring waters probably sometimes deposit realgar, stibnite, cinnabar, and gold.

Ores deposited from the true ore magmas have been deposited up to within 500 to 1,000 feet, or less, of the surface, as shown by a consideration of recent volcanoes and slightly eroded volcanic necks; but the true ore magmas do not reach the surface, breaking up when they reach a pressure zone very close to it.

IT MAY WELL BE that some of my readers, jumping to unwarranted conclusions, while perusing or skimming or skipping the previous chapters of this series of informal essays on ore deposition, have several times been moved to remark that my thought as to the nature of the ore-depositing fluids was extreme, and contrary to the evidence which may everywhere be observed, to the effect that ores are deposited from waters, either hot or cold, and of subterranean or surficial origin. To these

I now wish to remark that I have been describing what I believe to be the main and chief manner of ore deposition, and the nature and origin of the ore-bearing fluids par excellence, the ore magmas.

As for the rest, there are many other, on the whole, I believe, minor factors, but most important and necessary to know.

In short: every fluid (mainly water) that circulates through the rocks, or flows over the earth, or rests upon the earth, is a dissolving and precipitating agent, and performs work in taking into solution diverse elements, and in throwing them down again, usually in concentrated form. In that way a great number of commercially valuable deposits of various minerals are formed: by the medium of water, I mean—water in all sorts of receptacles or channels or bodies.

Where shall we begin? With the oceans, perhaps. Into the oceans have been brought in solution soluble elements which the inflowing waters have dissolved from all the rocks of all the continents, over and through which they have run on their course. The waters which enter into the sea, as you all know, are not waters which have only slipped daintily over the earth to the ocean: these waters have sunk into the earth and the rocks, worked through them, seeped out into stream channels at some lower level, and have thus aided the erosive wearing down of the earth's face, by dissolution. The Mississippi, for example, annually dissolves and carries into the sea about 136,000,000 tons of rock matter, more than a third as much as the matter which it carries in suspension (340,000,000 tons). Therefore, the continents are not only swept into the sea by running water, but they are also in part dissolved and carried there. From all the rivers that flow from all the lands the sea receives these enormous amounts of the elements into solution. Altogether, it has been estimated that annually 2,735,000,000 tons of solid mineral substances are thus added, in solution, to the oceans.

At the present time, it is estimated that all the sea water on earth contains 48,400,000,000 million tons of dissolved salts. Let us see. Here we have something interesting to consider. Placing together these two estimates, it would appear that an equivalent of the total salts of the seas might be contributed from the land waters in about 17,700,000 years.[1] But there is no reason, of course, to believe that the oceans ever were fresh. Mineral-bearing water is the natural state, fresh water the temporary state, produced by the chemistry of the atmosphere, which draws the water from the oceans into the air, leaving the salts behind. The original waters, as they gathered together on the face of the earth, must have been, for all that we can see, much like the water vapors which issue from volcanoes at the present day and which are accompanied by and eventually hold in solution a great deal of salts, so that the waters as far back as we can imagine their appearance and concentration must have been highly charged with substances in solution. Considering all of this, it is not so much the wonder that the sea water contains so much in solution, as that it is not altogether saturated. But sea water is generally not saturated with any of the substances which it holds in solution. Locally, it is true, in certain parts of the ocean (for the content of dissolved salts differs

[1] I cite the estimate of the total amount of dissolved salts in the oceans from Grabau ("Geology of the Non-Metallic Mineral Deposits," 1920, Vol. I, p. 49); and that of the total amount of salts in solution contributed by streams to the ocean, from Pirsson and Schuchert ("Textbook of Geology," 1915, pp. 43 and 152). The figure of 17,700,000 years which I get by dividing one figure by the other naturally does not check with the carefully worked out calculations which have been made by many scientists on the basis of dissolved sodium salts (not all salts, as in the figures above cited) contained in the seas, as contrasted with the sodium salts annually brought down by the rivers. These investigators selected sodium because the amount abstracted by precipitation from the oceans is less than in the case of other dissolved salts. G. F. Becker concludes, on this basis, that the age of the oceans may be between 50,000,000 and 70,000,000 years (See F. W. Clarke, "Data of Geochemistry," Third Ed., Bull. 616, U. S. Geological Survey, 1916, p. 153). But all these estimates are subject to the remarks which follow.

in different oceans and in different parts of the same ocean) the water is saturated with lime, and a direct chemical precipitate takes place for this reason, filling the interstices in coral reefs, and cementing shells and rocks on shores with lime carbonate. In sea water as a whole, however, the lime content is only about 60 per cent of the maximum possible.

Doubtless there would be a greater degree of saturation of various dissolved substances in the sea if it were not for constant precipitation, which goes on continually even without the necessity of a saturation point having been reached. The principal agencies of precipitation are organic. Many animals and marine plants have the power to extract lime from sea water, and the amount of work thus done is enormous. Thus limestones are formed—by the accumulation of shells and other organic skeletons thus made—which cover extensive areas, attain great thicknesses, and when elevated, in the course of time, with the heaving up of the stiff but uneasy crust, form one of the principal kinds of surface rocks, topping the continents. What a vast work is here performed by the sea's solution and precipitation, involving, not the formation of a few puny calcite veins, such as the rock-coursing waters make, but an enormous work of selective action, extracting the lime from all the rocks of the earth, to gather it into one vast deposit of mineral! And while these limestones may perhaps not be conveniently called ore deposits, they fall in the same category, for an ore deposit is really a highly concentrated deposit of a single element, gathered by some special selective force from the complex salts of the earth's crust, and of commercial value. Many of these lime (or calcium) deposits are of commercial value, and accordingly are used for building-stone, for lime used in cements, as a chemical in various processes, as a fertilizer, and in many other ways. Here, perhaps, we have the most widespread and the most familiar type of a commercial mineral deposit, and the clearest exposition of its origin.

Others of the multitudinous organisms which inhabit the

sea possess other powers of selective precipitation. Some precipitate only silica, like certain sponges, which draw from the water their internal spicules, or skeletons. Later, when the limy accumulations in the midst of which these siliceous remains lie have been elevated to rocks, the siliceous bunches are known as flint, and are gathered from the lime rocks, as from the chalk (lime carbonate) formations on the English coast; and this flint has many a commercial use.

Iron is also thus precipitated by organic activity, in the form of the silicates, especially glauconite, a hydrated silicate of ferric (or sometimes ferro-ferric) iron and potassium. This formation goes on constantly under favorable conditions, which have been found to be the quiet parts of the ocean near, and yet not too near, the land, in the outer fringe of the land-derived muds. Here the iron of the muds or of the sea water is fixed as a silicate by countless tiny organisms. Such deposits of glauconite have been found by dredging; when they are elevated into land rocks they form considerable masses, as, for example, in New Jersey, where their future is valued not as a source of iron but of potash. It is probable that other iron silicates are forming by a similar action in various places on the ocean bed. On the Mesabi range, in Minnesota, the world's greatest iron-producing region at present, I discovered in 1894 that the original mineral was a similar silicate, formed under the same marine conditions as glauconite, as evidenced by its now occurring as a bed with sandstone (now quartzite) below and shale (originally mud rock) above. The mineral is a hydrous ferrous or ferro-ferric silicate, and although it has not the composition of glauconite, it has its peculiar habit, optical characteristics, and distinctive mode of disintegrating into iron oxide and cherty silica. This mineral has been named greenalite. Also, in Lorraine, Switzerland, and neighboring districts important iron deposits consist partly of an iron silicate supposed to be a hydrous silicate of ferrous iron and alumina, having, like the other minerals mentioned, a granular oölitic (like the roe of fish) habit.

This mineral has been called chamosite. Professor F. W. Clarke, in his "Data of Geochemistry," observes, "Whatever the final conclusion may be, it seems clear that glauconite, chamosite, and greenalite, and, possibly, other allied silicates were all formed by similar reactions, different local conditions having determined which product should appear."

From many points of geologic similarity between the Mesabi ores and rocks and those of the other Lake Superior iron ranges, there is little doubt in my mind that all have had the same origin; and this determines, therefore, the greatest iron region of the world as of this nature. At the present time, be it understood, the iron that is mined is all in the form of oxide, the silicate being found only in occasional residual fragments or portions. The iron silicate has broken up into iron oxide and "cherty" silica, and these have segregated into bands, producing the familiar "jasper and iron" of some of the iron ranges, and further segregation of the iron into masses has produced the ore deposits. The same seems probably the history in Lorraine, where the second most productive iron field in the world is worked. These and other evidences lead me to believe that I have good grounds for the surmise that the greatest and most productive of the world's iron deposits have this marine organic precipitation origin.

Iron ores in commercial quantity are also formed by magmas. Some are segregated from basic magmas, or indeed represent a highly specialized form of basic magma; but they are most often titaniferous, and are not so valuable as the deposits whose concentration takes place in ocean and lagoon waters.

Not only are the principal deposits of iron apparently of sedimentary origin, being deposited, it seems probable, by the processes of organic chemistry, and through the presence of organisms and organic matter in a certain type of sediments, but this appears to be the case with manganese also. Like iron, important deposits of manganese have been

formed from magmatic waters, and occur in the form of veins of rhodochrosite or rhodonite—either pure, or as a common gangue of metallic minerals of magmatic origin. But manganese is closely related to iron, and occurs in conjunction with it, in its various forms of occurrence. In the Lake Superior region, the iron ores contain more or less manganese, and locally the manganese is segregated so as to form an ore. One of the Lake Superior ranges—the Cuyuna, in Minnesota—contains so much manganese in the iron as to be a low-grade ore of manganese, and in fact is the largest American reserve of manganese ore of this grade.

The manganese ores of the Appalachians form, in this connection, an interesting study. As the map (Fig. 82) shows, they occupy a definite belt running through Virginia and eastern Tennessee into Georgia. They occur here in a series of stratified rocks ranging from cherty limestones in the Carboniferous, through Devonian and Silurian sandstones, to Cambrian shales, argillaceous dolomites, and shaly quartzites.

Stose[2] enumerates, as general conclusions for the origin of the manganese ores of this belt, that the ores (which have been leached and concentrated in various forms, along fractures and fissures, along porous beds, etc., by circulating waters of atmospheric origin) were derived from certain sedimentary layers which were originally richer than usual in manganese; that the original mineral was probably a carbonate of calcium, manganese, iron, and possibly magnesium; that the beds which originally contained the manganese mineral occur at definite horizons; and that several of these are associated with unconformities at the base of a sedimentary series or with marked changes in character of sediments. The manganese in these cases is believed to have been derived, with other mineral materials, such as glauconite, phosphate, and iron, from the disintegration of rocks on an old land surface.

[2] STOSE, G. W.: *Eng. and Min. Jour.*, Aug. 7, 1920.

Note that these transition beds are, like the critical glauconitic iron-bearing horizon of the Mesabi range in Minnesota, shaly beds, as between quartzite and dolomite in the Cambrian, and between sandstone and limestone in the Ordovician—that is, they represent the outer fringe of fine land sediments. That manganese, as well as iron, is actually deposited under these conditions has been shown by dredging operations of the Challenger Expedition, under

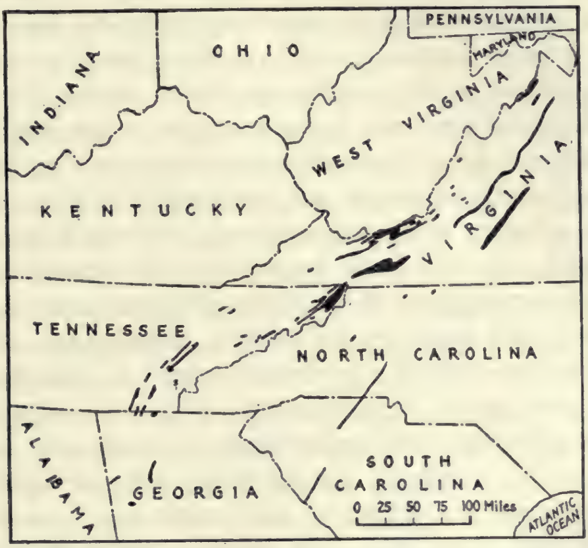


Fig. 82.—Southern Appalachian region; showing manganese ore areas, in formations varying in age from the pre-Cambrian to the Carboniferous. From George W. Stose: "Eng. and Min. Jour.," Aug. 7, 1920, p. 259.

Sir John Murray. That during all the vast time between the Carboniferous and the Cambrian sufficient manganese should have been deposited whenever there was sedimentation in this critical zone shows a constant supply, during all this time, of manganese-bearing mud from the land masses—a rather extraordinary supply, else why should this particular region be now manganese-bearing more than others which have had a similar sedimentary history?

In the Lake Superior region, the notable concentration

of sedimentary iron coincides with a notable basic igneous magmatic province, and the presence of basic lavas and intrusions, thereby indicating the source of the unusual supply of iron to the sedimentaries.

Iodine and potash are precipitated from sea water by marine plants, and become commercial sources of these elements.

Next we naturally turn our attention to the derivation of mineral deposits from the materials held in solution in smaller inclosed bodies of water—in lakes and lagoons and bogs. Here the action is much more active and complete, for on account of the smaller size of the basins, the waters are frequently enriched by evaporation, especially where and when the local climate becomes arid, so that the contents are easily separated and precipitated, either through organic agencies or by evaporation. Iron and manganese are thus deposited in bogs, largely through organic agencies. Lakes of various sizes, through evaporation, became supersaturated, and even dry up entirely, depositing, one after the other, those highly soluble salts which are not deposited in the open oceans. The principal of these is common salt (sodium chloride); then come magnesium chloride and sulphate, potash sulphate and chloride, lime carbonate and sulphate, sodium sulphate and carbonate, magnesium bromide, and other salts. In this way, by evaporation of lakes, the great salt deposits of the world appear to have been formed; and the chief mineral potash deposits of the world, those of Germany and Alsace, have the same origin. The different salts are thrown down one after the other largely in the order of their relative solubility, and, therefore, may often be mined separately.

Third, and very important, is the work of the atmospheric waters circulating through the rocks—the so-called ground water. Rain, constantly falling on the earth, soaks through the soil and into and through the rocks. Wherever this ground water is encountered underground, analysis shows that it is no longer pure, but has dissolved out material

from the rocks (principally silica, lime, magnesia, soda, and potash). Near the surface the solution is so great that the reduction of volume of the rocks is very considerable, and the rock softens and collapses, shrinking on itself. Depending upon the nature of the rock attacked, certain valuable mineral deposits are formed by this process, through the concentration of residual materials. A feldspathic rock, such as a pegmatite or a syenite, may become by this process china clay. These processes are mainly active in regions which have not been glaciated, and are most effective in tropical climates, where rains are frequently excessive and the temperature of the ground water and the rocks is warmer than in the north. Under these conditions kaolin (aluminum silicate) residual deposits, formed as above noted, may undergo a further decomposition to aluminum oxide, or bauxite, which is more easily reduced to metallic aluminum than is clay or kaolin, and thus is the chief source of that metal. Here is another important form of ore deposit due to the leaching and altering action of surface waters.

Manganese is concentrated by surface waters, especially in warm climates, as residual deposits; and most of the manganese deposits worked have apparently needed this action before they could be concentrated from their distribution in the rocks, to the condition of an ore. This, of course, refers to the oxide deposits. The carbonate (rhodochrosite) deposits, which are not so important, but which sometimes, as at Butte, become workable ores, are, of course, of vein formation, and are deposited by special (magmatic) solutions, like the metalliferous veins of the same districts. Manganese is one of the common elements in rocks, and the only thing necessary to form an ore is a process of concentration.

The phosphate of lime, which is one of our most valuable fertilizer minerals, in many cases owes its concentration, first to the precipitative effect of organic matter, and second to the concentration of the lime phosphate, thus formed, by

the effect of waters at the surface. Phosphorus is one of the most common elements in the earth's crust, ranking tenth in the order of abundance; by the wonderful chemistry of living organisms, it is precipitated in bones and in the shells and other parts of many kinds of living creatures. This lime phosphate accumulates as beds of hard rock, sometimes needing no further concentration; in other cases scattered phosphate nodules have been concentrated in streams, or as a residual deposit from the surficial decomposition and dissolution of the inclosing lime or dolomite. Enormous quantities are thus accumulated, and the deposits of phosphate so formed are by very far the largest and indeed almost the sole source of the mineral. Another type of lime phosphate has been formed from the porous limestone of tropical islands, to which has been added phosphorus derived from leaching of guano deposits. Nevertheless (as is the case with manganese and calcite, and also with iron), phosphate of lime, in the crystalline form, apatite, also occurs in veins, of pegmatitic or magmatic origin; and sometimes, as in Canada and Spain, these are worked as commercial deposits.

Magnesite, the carbonate of magnesium (valuable as a refractory material, and for use as flooring), is also largely concentrated by surface waters. Magnesium is the eighth element in order of abundance in the earth's crust. It occurs, largely, in the form of dolomite. Dolomite is the double carbonate of lime and magnesium, and is formed in various ways, by precipitation: through organic action, just as limestone is; in the open seas, or as a chemical precipitate in landlocked evaporating lakes. Magnesium is also one of the chief constituents of magmatic deposits, including some mineral veins, where it occurs mainly as carbonate; and especially it is a constituent of basic igneous rocks. It is in the latter in the form of silicate, and becomes a carbonate, and frequently segregates into veinlets of commercial value, during the thorough decomposition of the igneous rock, as in Greece and Asia Minor.

In Asia Minor, as I have myself observed, meerschaum (sepiolite, hydrous magnesium silicate) is formed by the alteration of the magnesite by surface waters. The mines of meerschaum of Eskishehir, in Asia Minor, are largely shallow pits in the detrital material or "wash," and I have noted in these pits boulders of magnesite altered from the outside inward, in all stages, to meerschaum. I do not know that this has been described before.

The formation of commercially important magnesite may also be accomplished by hot ascending waters. Dolomite frequently has this origin, through the addition of magnesium by hot-spring waters to limestone[3]; and Mr. Bailey Willis believes the great magnesite deposits of Washington have this origin.

It is the very commonest elements in the earth's crust whose principal commercial deposits are formed by surface waters, either from ocean or lagoon precipitation, or from the concentrating action of surface waters, leaching down in the decaying rocks and concentrating certain components. The commonest element in the crust is oxygen; next comes silicon, whose principal commercial deposits (as pure sand) are concentrated by surface waters, but by a mechanical, not chemical, process. Third comes aluminum, fourth iron, fifth calcium, sixth sodium, seventh potassium, and eighth magnesium, the commercial concentration of all of which is, as above noted, effected by surface waters, and directly from the disseminated form in the rocks. Ninth comes titanium, which is little used commercially, but when used is chiefly extracted from the oxide rutile, which is mainly concentrated from igneous rocks rich in the mineral. Titanium, being very refractory to solution, is not concentrated by surface waters. Tenth in order of abundance among the elements of the crust comes phosphorus, and twelfth (the eleventh being hydrogen) comes manganese, both, as above stated, chiefly concentrated into

[3] As I have shown at Glenwood Springs, in Colorado (*Monograph* XXXI, U. S. Geol. Surv., p. 212).

commercial deposits through the activity of surface waters. Fourteenth comes chlorine, also chiefly concentrated (mainly as salt) by solution in surface waters. Fluorine is thirteenth, and is only concentrated, as I believe, as a vein deposition from magmatic waters; it occurs chiefly as fluorite, the fluoride of lime; also, as a fluoride of soda and aluminum—cryolite—in one locality in the world chiefly—in Greenland, where it seems to have a magmatic origin.

Beyond these elements, however, in the scale of relative abundance, we find no elements which are mainly concentrated by solution in surface waters and redeposition in concentrated form. Only carbon (nineteenth) owes its vast concentration, as coal, to the power of organic precipitation, which collects it from the air and stores it in vast mineral deposits. Of the other elements rarer than chlorine, and varying in abundance from sulphur (fifteenth) to platinum (forty-fourth), there is none which does not owe its chief commercial concentration to magma action. Magma action is the great process whereby highly specialized magma solutions of each element are made, through whose precipitation highly concentrated deposits of each element have been formed. By this magma action are formed deposits rich in each of the commoner elements, although the same elements have been concentrated far more extensively through the agency of surface waters. Magma action, however, apparently finds no more difficulty in preparing highly concentrated deposits of the rarest elements, like silver (thirty-seventh), tungsten (thirty-eighth), gold (forty-first) or platinum (forty-fourth) than of the most abundant first fourteen elements; whereas the quantitatively abundant but chemically relatively simple surface waters appear entirely unable to effect, from disseminated form in the rocks, the degree of concentration necessary to collect enough of any but the commonest elements to form a commercial ore deposit. It was formerly, and not so very long ago, believed that this (the concentration of the rare elements into ore deposits by surface

waters) could be done, and that it is in fact the main process of ore concentration. It was believed, following the discovery that the rocks contained, at least in a disseminated form, every element, including the most rare, that the surface waters, sinking into the rocks, and permeating them along fissures and crevices, leached the elements out and precipitated them along the main fissure channels in highly concentrated form, thus producing mineral veins. Such was the belief of Sandberger in Germany, and of various geologists in America. These views in general are, it seems to me, untenable, and without adequate evidence; they are now held only here and there.

It is true that there are occasional minor deposits of a few of the rarer minerals which are formed by concentration by surface waters of the elements in the rocks. This is true of some relatively minor nickel (twenty-first in order of abundance) deposits; but these deposits have been concentrated from nickel-rich magmas by surface waters, and are residual, practically as are the residual types of manganese and other ores described above. That there have been important deposits of any of the rarer elements due entirely to this process of concentration by ordinary ground waters, however, I do not for a moment believe. Such an origin has been argued especially for some important lead and zinc deposits, in the Mississippi Valley; and for some copper deposits which occur in sedimentary rocks, none of which are very important. As I have repeatedly stated, I do not entertain the suggestion for the lead and zinc deposits; nor do I seriously consider it for the copper deposits in question, among which is the celebrated instance of the copper-bearing shale at Mansfeld, Germany.

The surface waters, in the ocean and in rivers, are potent in concentrating ores also by a process of which they have the exclusive use among waters—that of mechanical concentration or ore dressing. Waters as solvents may concentrate ores by the "wet process," whether on the surface of the earth, or near its surface; but only at the very

surface can take place those operations which are a natural form of "milling." By the threshing of the surf up the long flat sandy shore, by the milling and churning and grinding of the pebbles and clay by the flow of the inland stream, rock material is ground, mixed, and thoroughly concentrated by gravity, or, in part, by relative hardness. Many individual products are thus segregated and aggregated, and some in commercial quantity and of commercial quality. In the watersheds of many rivers are gold-bearing veins, and along their beds the heavy gold will become concentrated. Such is the origin of placer gold, one of the chief sources of the metal; also of placer tin ("stream tin"), in which form also a great deal of tin is recovered. Gold placers occur in the beds of present streams; and old stream channels belonging to an earlier period, such as the Tertiary gravels of California, are now raised to form part of the mountains and are locally capped by lava flows, so that the gold-bearing gravel has to be reached by rock mining. Such mechanical concentrations of gold may be rehandled (as it were), mechanically, by streams, repeatedly at different geological epochs: the gold will neither noticeably wear out, nor will it appreciably dissolve away, under ordinary conditions. Therefore, we have what to the layman is always the puzzling spectacle of rich placers in a region of unimportant veins, as in the Klondike-Yukon region of Alaska and British America. In Alaska, also, at Nome, in this same gold belt, where the original veins occur in schist, is the richest recorded instance of placer-gold occurrence on marine beaches; here the raising of the land by repeated uplifts during recent and Tertiary time has left a succession of old beaches, covered with gold-bearing gravels. In river gravels nearly the whole platinum supply of the world is found, in placer form, mainly in Russia and Colombia; and a little occurs in beach placers.

Besides gold and tin, other valuable minerals are thus concentrated. Zircon, the silicate of zirconia, a constituent

of granites and pegmatites, a hard mineral which does not decompose, has its principal commercial stores in the sea beaches of India and Brazil. In Brazil it occurs in great sea-sand deposits along the coast, where it has been concentrated through the double effect of deep disintegration and shriveling of the contained rock under the corrosive influences of a tropical climate, and mechanical concentration of the resistant residual minerals by the milling process of the surf. In the same deposits occur the world's principal supplies of monazite. Zirconia is used mainly as a refractory; and monazite as a source for the elements thorium and mesothorium, the former used for the mantles of Welsbach lights, the latter as a substitute for radium (for luminous paints and for medicinal purposes).

Along sea beaches, also, the iron in sands—the scattered hematite and magnetite which occur in nearly all igneous rocks—are concentrated in these surf mills; and such "black sands" in places become nearly or quite commercial sources of iron. They have been worked in Japan.

To the type of mechanically concentrated deposits belong practically all our commercial deposits of silica, concentrated as clean white sand in the marginal sea-mills. These, formed on the characteristic vast scale of the surficial deposits, represent a very important type of commercial mineral deposit.

Reviewing the work of the superficial waters—those resting directly upon the surface of the earth—in dissolving scattered elements and precipitating them in concentrated form, we perceive a natural earth zone of great chemical activity—the zone of chemical reactions between the atmosphere and the solid rock crust. This zone is not a thick one: it embraces those bodies of standing or running water which overlie the rocks; and, as we all know, it goes down a little into the rocks, by virtue of the penetration of these same surface waters, forming in them the familiar zone of oxidation.

These superficial waters appear, as I say, to obtain their

powers of concentration mainly through the changes due to reaction between the air and the rocks. And the most powerful reagent is living organic matter. This agency has made possible the limestone deposits, most of the iron ores, the coal deposits, probably the petroleum deposits, the phosphate deposits, and others. The bulk of deposits of this type is on a far grander scale than any other form of ore deposits: but, as I observed before, only the commoner elements are thus concentrated.[4] This method of concentration is, of course, eliminated from the uninhabited region of the subsurface rocks.

Another important group of ore deposits belonging to the reaction zone between the air and the rocks are those deposits which we have just mentioned as due to the evaporation of lagoon or lake waters. Thus are produced our great deposits of salt, potash, probably of gypsum, etc. These again concentrate only the most common elements in the crust, but on a magnificent scale.

Ore deposits of the mechanically concentrated type, including, as above mentioned, mainly gold, tin, platinum, zircon, monazite, and other placers, also constitute a special and important type, and one which naturally is eliminated from those deposits formed in the rocks.

The fourth group of deposits belonging to the atmosphere-crust reaction zone is the so-called residual deposit, formed by the selective action of surface waters in the zone of oxidation, eating down, dissolving and carrying down and precipitating, and thereby effecting a rearrangement of the elements in the thoroughly altered weathered zone of rock. This group is characteristic mainly of warm lati-

[4] Organic matter can exist and survive only at the exact contact of atmosphere and rock, so is the product of the most intense and active chemical reactions resulting therefrom. We, ourselves, exist, breathe, work, and think by virtue of these complicated and intense chemical reactions. We inhale oxygen and exhale carbonic acid. Our feet are on the ground, and our heads in the air. We cannot exist if permanently removed a few feet up or down from the earth's surface, for the necessary chemical reactions between atmosphere and earth could not then take place.

tudes, where the chemical reactions between air, water, and rocks are more powerful. Such are the bauxite deposits, the clays, certain manganese deposits, and others. Like all the atmosphere-rock contact-zone deposits, they are on a grand scale; like all except the mechanical type of these deposits, they concentrate almost exclusively the commoner elements.

It will be seen that the surface waters do wonderful work, through their power of dissolving and precipitation, in producing our chief deposits of the very common elements; and, through their mechanical power, of some of our rare metals and minerals which happen to be non-corrosive—not attacked by chemical action. Now, these waters penetrate the rocks below the surface: we find them running through fissures (water-courses) hundreds of feet below the surface. What work do they do below the zone of oxidation—below the zone of chemical reactions between the atmosphere and the rocks? To the best of my belief, little or nothing: to the best of my belief they do not, below the zone of chemical reactions between the atmosphere and the rocks (which zone I conceive of as at most only a few hundred feet thick), create, by themselves, any mineral or metal concentrations of commercial value whatever, *of any element, no matter how common.* In my estimation, the waters of the earth's surface are shorn of their strength as Samson was of his locks, when they leave the society of the air, with which they work on the surface and in the shattered rocks near their outcrops.

I know that these waters are not entirely inert. I know that along water-courses they tend to leach the rock and soften it, and thereby themselves become laden with salts of the commoner elements; but I think that is about all they do along fissures. I have never seen any evidence of their precipitating anywhere underground any concentrated element. If they did, it would naturally be mainly deposits of the commoner elements, such as lime, silica, iron, magnesium, aluminum, etc. We do not find such universal

deposits, under these universal circumstances, formed as veins in fissures, or as replacements of solid or shattered rock. As a matter of fact, students of mines know now that the rocks are pretty tight below the zone of weathering, and being pretty tight, they are pretty dry; not much water, or in some cases none at all, works down into them. The water which sinks into the shattered, shrunken, alteration-undergoing rock near the surface, therefore, mainly flows off laterally, finds its way into stream valleys and so into the sea, with its burden of salts which it has dissolved from the rocks. Below this zone the rocks are relatively safe, with their treasures, from such marauding waters, except along occasional fissure channels or porous beds. The great mass of rocks is not searched by ground waters, as we once imagined, and their daintiest and tiniest treasures of gold and silver robbed. If this were done—if veins of gold and silver and copper were thus concentrated—how is it that the commoner elements have not been transferred and concentrated into commensurately vast deposits, as they are on the earth's surface, in the active reaction-zone between the earth and the air? If such common elements, which we know go into solution, in such deeper surface-derived waters, along water-courses, are not found concentrated thereby on a grand scale, what warrant have we for believing that all the rare ones have thus been marvelously concentrated? If iron, which constitutes 5.12 per cent of the earth's crust, and which is dissolved by nearly all circulating waters, is not thrown down by these waters and concentrated into vast commercial deposits in these deeper zones, what reason have we for claiming that copper, which makes 0.002 per cent of the crust, or gold, whose percentage is expressed by Washington by the decimal 0.000000xx per cent, has been thus concentrated into great veins and orebodies, on a truly stupendous scale?

I am not merely carping at others when I marvel at these theories: at the imaginative excesses of the conservative, the fairy stories of the young investigator who sees witches

riding the air on their broomsticks where the next generation of investigators will see nothing at all. Already we smile at the explanation of the glacial drift and the fossils in the rocks, as the work of the Great Flood; or the theory that fossils were the work of a mysterious impulse in nature, which wrought in rocks what under more favorable circumstances—given plenty of air, perhaps—would not have been still-born as fossils, but have lived as healthy clams and fishes. Well, as I look over the evidence, I cannot see the theory of the formation of mineral veins—veins of gold, silver, lead, and copper—by atmospheric waters, dissolving out the minute content of the rocks and precipitating this in concentrated form along fissures—as any more firmly sustained by evidence than any of these old theories. I cannot see that the belief—your mistake and mine—rested on any proper evidence at all.

What alchemy—not chemistry—enabled the hypothetical searching waters to dissolve out of the innermost rock its gold and silver, and not its lime, soda, potash, iron, magnesium, and the rest? What kindly hand guided the solutions from whatever source, so that they should not lose their way, and so all passed through the little fissure which should ultimately become a vein? What voice of conscience spake to them as they were passing through and told them that now was the time to drop the gold and the silver? "I realize you are far from being saturated" the pleasant voice might be imagined to say—since we are dealing with fairy tales—"and that you hold only one umpty-millionth part of gold in solution. I realize that far from dropping that little amount, you would be justified by the laws of chemistry in swiping something of what has already been left in the contribution box by the solutions which have preceded you: but drop your mite anyhow, else we shall never have a vein at all, and shall be driven to a new theory." What devoted gnomes warned the waters as they approached: "The copper vein is forming on the left; the fluorite vein thirty feet beyond on the right. Waters carrying copper please

separate from those carrying fluorine and lime, and see that you get to your respective fissures, or the unity and artistic completion of veins will be lost." And afterward the word would go around: "The copper and the fluorite veins have both been completed; all hands now turn to and fetch barium from the rocks for the barite vein which has just been laid down to intersect both."

No. First, to have the metals gathered from the rocks, the rocks must incidentally have been reduced practically to an insoluble residual clay. Theory is hardly necessary to arrive at this conclusion; we see the workings of it in the zone of weathering—the only zone of complete rock-searching by solutions that there is. Below the zone of rock-weathering, rocks are not usually found in such a condition; normally, and in all except an infinitesimal percentage (chiefly in connection with the passage of magma solutions), they are hard and unaltered—they still hold whatever the Lord gave them in the beginning, whether of lime, soda, lead, or gold. Therefore, the crust has not been ransacked. Again, as I remarked above, circulating waters are not present in many of these deep rocks, even in the fissures. Third, where we find fissures, or water in the fissures, nobody ever really caught this fairy leaving the gold, or building up a metal vein. If veins were formed by this uniformitarian process, we should find—since there are metals in all rocks—metal veins in all stages of growth in all rocks. But we should then be no happier, for we should have still to solve the new chemistry whereby the rarer metals were concentrated along fissures, and the common and easily soluble elements were not taken into solution at all, thus upsetting the laws of nature.

What really happened to our mental processes, of course, was the old story that we had an actual fact to begin with—veins of silver, gold, copper, and zinc—and we had to find an explanation for them; and, as mankind has done from the beginning, we ascribed the result to processes with which we were most familiar: to atmospheric water, which we

knew could dissolve and precipitate. When Sandberger found metals were present in the rocks, our imaginations leaped among these three facts—veins, water, rocks—and tied them all together across the yawning chasms of improbability. Afterward, when we found the veins clustered around igneous rocks, we built a new theory and reluctantly and piecemeal scrapped the old: but to this day, if the igneous rock does not actually poke its head among the veins, and sometimes even if it does, we stick to the religion of our fathers.

Exit, then, and *vale*, so far as I am concerned, the underground surface-derived water below the superficial rock zone as a cause of the primary concentration of ore deposits. I believe that this cause is negligible. Exceptions, which would seem to prove me wrong, and which will at once occur to many of my readers, will ordinarily be found to be characteristic of the zone of atmosphere-rock reaction. Such are the instances of the formation of sulphides in old workings, covering old tools. In addition—there was a preexisting orebody.[5] The lime stalagmites in caves are the result of atmospheric reaction: the caves are filled with air.

[5] The deposition of ore deposits by surface or ground waters is thought by many to be proved by the recorded cases of deposition of sulphides, such as those of lead and zinc, in old mines. Such a case was reported from Missouri, where galena was found deposited on an old iron pick; and more recently H. A. Wheeler has described (through the *Trans.* A. I. M. E., Feb., 1920, LXIII, 311) in Oklahoma, the deposition of galena, in crystals up to half an inch long, on an iron spike, in the space of two years that the mine was under water.

Such observations only confirm what has been decided from geologic evidence in most ore deposits—the formation of secondary minerals (including secondary sulphides) by surface waters. In most cases, however, it is plain that these surface waters have gained their metallic content from primary ores of deep-seated origin, and there seems to me no evidence that such is not the case in Missouri and Oklahoma.

As I have explained in the case of certain veins at Georgetown, Colorado, there are instances where this zone of secondary ores, migrating downward as erosion progresses, overtakes and passes beyond the bottom of the primary orebody, so that the orebody we now find is entirely of secondary nature, and deposited from descending waters: but that such descending waters have ever concentrated from the rocks a primary ore

But in addition to descending waters in the rocks, there are more rarely ascending currents. These may be artesian—that is to say, surface waters, which, on account of hydrostatic conditions, rise, after having descended by another channel. Such waters may be cold or lukewarm; possibly warm. What effect have they in ore deposition? So far as I have seen evidence, no more than have the descending or lateral-flowing waters of the same atmospheric origin. Far from artesian waters being clogged with copper, lead, and antimony, and the rest of the materials for mineral-vein formation, we find such waters remarkably pure and potable. A country estate, or even a suburb, which has artesian water, rightly congratulates itself. Around the orifice of such an artesian spring, where it strikes the air, no mound of sinter stained with rare metals is built up, no precipitates of the uncommon metals are discharged. What effect could such water be supposed to have in cementing shut the airless fissures through which it moves? These spring waters, to be sure, do carry minerals in solution, even iron; but show only, therefore, the results of a little leaching along their channels, and are always very, very far from saturation. Do artesian waters cement shut the pipes through which they reach the surface?

Let us next consider another and special type of rock-traversing solutions—hot springs. There is now a rather general agreement that much if not most of this hot water is direct magmatic water given off from slow-cooling igneous rocks in depth; although some atmospheric water may well become mingled with it. Hot waters, we know, are more powerful chemically than cold ones; and this is shown by these springs building up around their orifices mounds of material which they precipitate when they touch the atmosphere. Such deposits consist of silica and lime, mainly. Mexican onyx, which is lime colored by a little iron, formed in beautiful concentric rings of successive depo-

---

deposit of copper, lead, zinc, or the rarer metals, I do not believe, for I find no evidence of it.

sition, is a commercial type of mineral deposit formed in this way; but please note that it belongs to the atmosphere-rock contact-zone phenomena. Traces of metals rarer than iron are also found, including gold and quicksilver; but no deposit of metallic minerals even remotely approaching commercial importance has ever been formed in this way.

What effects have such waters in the fissures through which they pass? Do they deposit vein material and form veins? On this point we have not much evidence. (You will be surprised at that statement; and the conclusion has been surprising to me.) The hot-spring waters encountered in the Comstock mines are not forming veins: they are dissolving rather than precipitating. The warm waters of probable magmatic origin found in depth in the Tonopah mines are likewise leaching the rocks (near the water channels only), not cementing. These leaching effects and chemical changes involved must, of course, be more active in the case of hot springs than of other waters; and certain chemical changes, like dolomization (the substitution of magnesia for lime in limestone wall rock), take place, as I have shown at Glenwood Springs, in Colorado. Very near the surface, where contact with the atmosphere is already established through crevices in the rocks, occasional veins of calcite may be formed, with a little of the carbonates of magnesia, iron, etc. Hot-spring waters are characteristically (and naturally) full of mineral substances, mainly, of course, lime, magnesia, soda, potash, iron, and the rest of the commoner (and soluble) elements. Sodium chloride, sodium carbonate, and sometimes sodium sulphate are the predominant characteristics of certain of these springs.

In so far as these hot-spring waters are of magmatic origin, they are, of course, related to the ore magmas which I have described as the vehicle through which deposits of the rarer elements are mainly brought into being. And when we find traces of metals in the sinter and in the rocks around some of these springs, as at Steamboat Springs, the Yellowstone, and Sulphur Bank in California, we are at

first quite ready to believe that here we really have, visible and on exhibition, the special magmatic agent which has formed mineral deposits. Around Steamboat Springs, mercury sulphide (cinnabar), as well as antimony, arsenic, and sulphur, and traces of other metals, are being deposited in the sinter. At Sulphur Bank, cinnabar and sulphur are being deposited. The borates which occur in these waters are evidence of their magmatic origin, since this element is one of the most characteristic of volcanic exhalations, and is otherwise chiefly characteristic of certain magmatic minerals, like tourmaline, formed in depth especially in connection with magmatic activity. Indeed, hot springs of this type and volcanic vapors are plainly very closely related, so much so that the latter may be considered a vaporized phase of the former, and both may be referred to the same type and stage of solution. The volcanic vapors are, of course, more active in their work.

From volcanic emanations, which when they encounter the atmosphere undergo the reactions due to this contact, a special array of ore deposits are formed: but it must be noted again that these deposits are characteristic of the atmosphere-rock reaction zone, and cannot with confidence be assumed to take place in depth. Among such deposits are sulphur, boric acid, ammonium chloride, potash alum, and others. These deposits frequently show small amounts of various metals, including cinnabar, arsenic, cobalt, zinc, tin, bismuth, lead, and copper; but the metallic deposits are of no commercial value whatever.

Non-metallic salts, similar to those formed around volcanoes by the fumaroles, are also formed by hot springs. It is possible that the nitrate deposits of Chile are due to volcanic hot springs or to volcanic vapors. Opinions about that differ very widely. Lindgren states his belief in such an origin,[6] but they have been explained in many other ways. They have been regarded as having been fixed from the air by electric discharges, or as having been fixed in

[6] "Mineral Deposits," 1919, p. 299.

the soil by organic matter and bacteria. Certainly their preservation is due in large part to the arid climate.[7] Their frequent association with borates, however, seems to point to an original volcanic origin.[8]

The deposits of this type—the fumarole-hot-spring type—show by their concentration of the rarer elements that they represent the processes of magmatic segregation; and are thereby contrasted with the processes characteristic of the surface or atmospheric waters, which, as above emphasized, deal with the commoner rock-forming elements in the earth's crust. Boron, for example, is twenty-eighth in the list of elements making up the crust, standing between cobalt and zinc; and, therefore, its concentration by fumarolic activity in abundance and in commercial quantity, as around the crater of Vulcano and in Tuscany, or from hot springs, as in Northern India, is of a type of segregation approaching that which has produced our main type of underground ore deposit, such as our veins containing gold, our veins of silver, our veins of antimony, etc. Nor is there any doubt, I think, that borax deposits in general, which are sufficiently abundant so that borax may be used as a cheap and every-day chemical, have this same direct magmatic origin; and this is true of the borax deposits of California and Nevada, including the playa deposits, as I have long ago pointed out.[9] Whatever the origin of the Chilean nitrates may be, the concentration of nitrogen in fumarolic and hot-spring deposits, in the form of ammonia salts (chloride), as deposited around many volcanoes and also in connection with the Northern India hot-spring borax deposits mentioned above, is eloquent of magmatic differentiation. We are familiar with the nitrogen of the air, which becomes fixed in the soil by the power-

[7] GRABAU, A. A.: "Geology of the Non-Metallic Mineral Deposits," 1920, p. 295.

[8] I have argued the volcanic origin of the principal nitrate deposits in an editorial in *Engineering and Mining Journal-Press,* Vol. 114, p. 969.

[9] *Professional Paper* 55, "Ore Deposits of the Silver Peak Quadrangle, Nevada," U. S. Geol. Surv., 1906.

ful processes of organic chemistry; but these volcanic and hot-spring concentrations of nitrogen come from the depths of the earth—are in fact derived from the rock substance or buried magma of the earth. It is, of course, easy to pass from this consideration to the logical surmise that the nitrogen of the atmosphere represents just this magmatic segregation, poured out from the volcanoes and fumaroles of all time, and retained as a gaseous blanket over the rocks of the earth's crust, holding its position above the waters and the rocks by its relative specific gravity. Indeed, the same line of logic leads to the recognition of the same origin for the atmospheric waters, including the oceans.

Since many of our spring waters, including warm-spring waters, are probably of mixed origin, some being directly magmatic and others mixed with waters of direct atmospheric origin, or entirely of direct atmospheric origin, the test of the content of rare elements may often be applied. For example, in the table of spring waters of disputed origin, given by Grabau,[10] the waters of Yellowstone Park show, by their content of arsenic, boric acid, and ammonia, their magmatic origin.

Having recognized such ascending mineral waters, of magmatic origin, bearing frequently rare magmatically segregated elements like boron—are we to conclude that we have here the ore-depositing fluids, from which the metallic-mineral veins in general have been deposited? From the traces of metals found in these waters, from the similar traces in their sinters, and from the small occurrences of metallic minerals in volcanic craters we have been accustomed to conclude that here we have under our eyes the "mineralizing solutions," the ore magma itself; and underground, if we, very rarely, as in the case of the Comstock, found hot waters circulating along the vein of silver, gold, lead, and zinc, we have had no doubt that this was

[10] "Geology of the Non-Metallic Mineral Deposits," p. 329.

evidence that the metallic minerals were formed from such waters.

But, examined carefully, our evidence connects these Comstock waters more closely to cinnabar deposits, and by this very fact removes them from the more ordinary type of ore deposits. At Tonopah, in Nevada, I have noted cinnabar only in one place, coating joints in the veins; and evidently belonging to a far later period than the gold-silver ore deposition. Stains of cinnabar I found in a deposit of alum (kalinite), sulphur, and gypsum near Silver Peak.[11] These deposits are such as are typical of hot springs at or near the surface. The deposition of cinnabar from existing hot springs, as at Steamboat Springs, falls in line with these observations, to indicate that cinnabar is really deposited from such hot springs, and near the surface. Lindgren, however, justly observes that "no cinnabar deposit has yet been found to change gradually into ores of different character as depth is attained. No deposits have been worked below a depth of 2,000 feet vertically beneath the croppings." It must be noted, moreover, that cinnabar does not occur in dike-like veins, as do so commonly the ores in general, but as incrustations and impregnations, an occurrence quite in keeping with the belief in its deposition from hot-spring waters.

In California and Nevada, all the indications point to a Quaternary or Recent age for the quicksilver deposits, and an association with the present known hot springs. Therefore, the existing hot waters of the Comstock Lode would be correlated with this Quaternary-Recent quicksilver deposition; and not with the entirely different Middle Tertiary silver-gold deposition. The present circulation of hot waters along the lode would then appear to be quite fortuitous, and to have no necessary genetic connection. A mineral vein is always a line of weakness, and generally subsequent movement has opened up a fissure along it; it,

[11] "Alum Deposit Near Silver Peak, Esmeralda County, Nev.," Bulletin 225, U. S. Geol. Surv., p. 501.

therefore, becomes the natural channel for circulating waters, hot or cold, ascending or descending: but we must beware of arguing genetic connection for that reason.

The temperature of many of these hot springs, like those in the Yellowstone and those at Sulphur Bank, is around the boiling point, or about 200° F. or nearly 100° C. Under such conditions cinnabar is deposited. If, however, we assume an increment of temperature in depth, the average temperature of the vertical zone of about 2,000 feet through which cinnabar deposits have been mined would be considerably greater. If we allow an increment of 1° F. for each 100 feet, which has been established in some non-volcanic regions, we should have at 2,000 feet a temperature of, say, 230° F. But in volcanic regions the increment is higher. In the Comstock it is 1° for each 33 feet; and I have found a similar condition at Tonopah. This would give a minimum temperature of about 270° F., or about 132° C., at the bottom of the zone. Around the fumaroles of volcanoes, cinnabar and realgar are deposited, at temperatures not definitely determined.

In cinnabar deposits the common gangue minerals are chalcedonic silica and calcite, with frequently barite and gypsum. Fluorite is rare. Adularia has not been noted. At Steamboat Springs, in Nevada, the waters contain principally sodium chloride; at Sulphur Bank, sodium carbonate and sodium borate. Of the other metallic minerals found with the cinnabar deposits, antimony sulphide or stibnite seems closest related, and has been noted at Steamboat Springs by Lindgren: realgar is sometimes associated.

There are rare ore deposits, but of a very peculiar and characteristic type, which appear to connect the cinnabar (mercury) deposits with certain gold ores. I have seen only two deposits of this type. The first I have described from Mercur, Utah, where shales and a porphyry sheet are impregnated with gold, associated with realgar and cinnabar. The mine was early worked for quicksilver, and later became an important gold mine. The other deposit is the

White Caps mine, at Manhattan, Nevada, which I have briefly visited, and which has subsequently been studied by Mr. H. G. Ferguson.[12] The White Caps mine resembles the Mercur mine in containing gold ores impregnated in limestone, and associated with realgar and some cinnabar. Ferguson has described two distinct stages: first, arsenopyrite, pyrite, gold, and fluorite; and second, realgar, stibnite, and gold. The gold and realgar of the second stage is believed to have been derived—though probably through the agency of ascending solutions—from presumably auriferous arsenopyrite of the first stage. The gangue minerals of the first stage are quartz and calcite, fluorite, leverrierite (hydrous aluminum silicate), and a little adularia. Ferguson did not have the opportunity to study the cinnabar, which is apparently similar to the realgar in age.

The recorded data indicate to me a lesser temperature for the second stage of deposition—a temperature marked by the deposition of stibnite, cinnabar, and (secondary) realgar; a stage comparable in temperature to that of mercury deposits in general, or of antimony (stibnite) deposits in general, which latter appear to represent a deeper and somewhat higher-temperature stage than the quicksilver deposits but to be closely connected with them: but the primary gold deposits at Manhattan—auriferous arsenopyrite, fluorite, and adularia—seem to me to represent an altogether deeper and higher-temperature deposit. This relation, the absence of adularia and the rarity of fluorite in these cinnabar-realgar deposits, and the characteristic occurrence of these gangue minerals—especially the adularia—as a gangue of the silver-gold veins of the Tertiary type—strengthen my belief that I have mentioned in Chapter VI, that adularia has not usually been deposited at a low temperature. The local evidence, moreover, that these cinnabar-realgar deposits, which go at least 2,000 feet in depth in the White Caps mine, are decidedly more super-

[12] *Econ. Geol.,* Jan., 1921, Vol. XVI, No. 1.

ficial in character than the primary gold-bearing veins, gives some hint of the relative depth of formation of the latter.[13]

Hot springs which emerge at the surface, such as those which deposit mercury, contain frequently a great deal of silica. Steamboat Springs water carries 11.41 per cent silica (percentage of the total impurities); some of the geyser waters in Yellowstone Park (Old Faithful) as much as 27 per cent. This is a sodium chloride water. The waters of the Grand Geyser, in Iceland, contain 45 per cent silica: this is otherwise a sodium-chloride sodium-carbonate water.[14] The solfatara (volcanic water), at Pozzuoli, Italy, contains nearly 13 per cent silica, and is otherwise a sulphuric acid water, containing practically no alkali.[15]

However, all the solid matters in these springs form but a very small amount, relative to that of water. In Steamboat Springs the total impurities are only 2.85 parts per thousand; in the Old Faithful Geyser, 1.39 parts; in the Grand Geyser of Iceland, 1.13 parts; the solfatara of Pozzuoli, 2.48 parts. These waters must then be far different from such a siliceous magma solution as has penetrated the volcanic rocks at Tonopah as an intrusive veindike (p. 154); and indeed from all those deeper magma solutions which have performed this same rôle, and formed dike-like veins in depth, of gangue minerals, or of metallic sulphides, or both.

Even many well-banded or well-crustified veins must,

[13] Tentatively a temperature for the ores of the first period (based on the presence of adularia—see Chapter VI, p. 303) would be around or above 340° C.; that of the second period, based on rough considerations just outlined, 100 to 150°. A wide divergence, between the deposition of arsenopyrite (at a high temperature) and realgar (at a low temperature) is thus indicated.

[14] GRABAU, A. A.: "Geology of the Non-Metallic Mineral Deposits," 1920, p. 329.

[15] It has been determined that the normal state of volcanic solutions is alkaline, and that the acids are the products of decomposition within craters or near the surface, by the action of steam on chlorides and sulphates. Native sulphur is also a decomposition product characteristic of this superficial zone, due largely to the decomposition of H_2S (sulphuretted hydrogen).

I believe, have been formed from a highly saturated ore magma, in which the amount of water was perhaps hardly, or not greatly, more than enough to hold the solids in solution. Examination of many of these veins shows angular included fragments of the wall rocks (Chapter II), showing that the nature of the ore-magma solution was such as to support inclusions; and the fine banding, sometimes surrounding these fragments as a center or building out from the walls, shows a rapid rhythmic precipitation of the various constituents. Such was the structure, for example, of the rich West vein in the Esperanza mine, at El Oro, Mexico (Fig. 70). This fine and rhythmic crustification may often be a minor feature, and represent a later crystallization stage of a vein which is mainly massive and homogeneous, as in the case of the Montana Tonopah vein at Tonopah, Nevada (Fig. 83). Such well-banded veins, or well-banded portions of veins, must represent a relatively more fluid ore-magma solution than the homogeneous veins, and they are frequently very rich, being perhaps not so much choked up with silica as some of the less hydrous ore magmas.

In seeking for and studying crustification in veins, other and quite distinct banded structures must, of course, be disregarded. Such are afforded by repeated reopenings and recementations, forming a compound vein of frequently diverse and rudely banded structure: or again by flow structure, as in the case of the Mandy ore (p. 115).

The conclusion that I am working to is that hot-spring magmatic waters, even when they deposit cinnabar and traces of other metals, or siliceous or calcareous sinter, do not represent the typical ore magmas which have formed veins in depth; but are, perhaps, the aqueous residue from such magmas, which magmas, although they may be characteristically much more aqueous than rock or dike magmas (true igneous magmas), yet differ in this respect a great deal, varying from aplitic or relatively dry vein magmas, to pegmatitic or relatively aqueous vein magmas, and

further to highly gaseous-aqueous or superpegmatitic vein magmas; but in all cases are quite different from the magmatic waters of hot springs. However, I do recognize

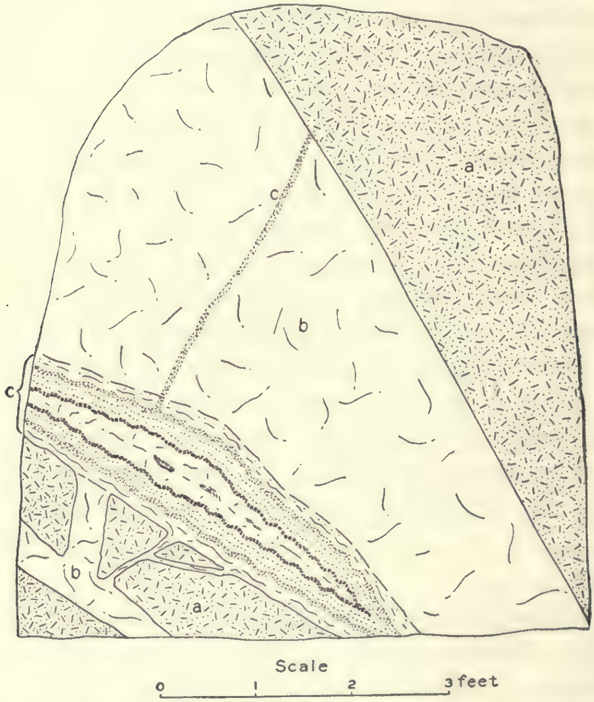


Fig. 83.—Drawing of face of Montana vein, Tonopah, Nevada. To illustrate filling of fissure *(c)* with finely banded high-grade ores, subsequent to the formation of the main lower-grade vein *(b)*, but within the period of primary ore deposition. Within the banded fissure-filling *(c)* are alternating fine bands of rich black argentiferous and auriferous sulphides, with quartz and carbonates. In the central quartz band are druses lined with adularia crystals. This banded deposition is believed to represent rhythmic or pulsating deposition from a highly concentrated solution which filled the opening. *a,* Andesite wall rock. J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Fig. 61, p. 171.

in these latter the probable mother-solutions of certain cinnabar deposits.

Often, however, residual magmatic waters accomplish, I believe, little or no mineralization, although they may

travel a long distance before reaching the surface. Nor do I believe that unless they carry from their source sufficient metals in solution to form an ore deposit they are able to do so by leaching the metals from the rocks through which they pass, and concentrating such metals along their channels. Examined carefully, we find no evidence of any such action. Therefore, I believe that even these hot magmatic waters are inert as to concentrating and forming ore deposits, unless they derive their metal contents from the processes of magmatic segregation. In and by themselves, I mean, I see no evidence of their having any such rôle; any more than do the artesian waters or the descending atmospheric waters; although were such a rôle possible to any of these, it would, of course, be to the hot ascending waters.

The fine and rhythmic banding which I have mentioned above as especially noticeable in certain veins which are formed in the upper zones of metal-vein formation, or in certain parts of such veins, is not usually of such type that it can be referred to a gradual filling of a fissure, by deposition along the walls from circulating fluids, and a consequent building up from the sides to the center. The banding is often exceedingly fine and delicate, and the metallic minerals—sulphides or even native gold—alternate many times with bands of gangue material, such as quartz, rhodochrosite, or other gangue. A pulsating or rhythmic precipitation from a constant solution is indicated. Characteristically the banding is finer at the walls or at the contact of fragments of country rock included in the vein, and wider spaced further away. Some veins of this type contain included angular or subangular fragments which do not touch the wall rock, and so cannot have been supported. The uncorroded shape of these angular fragments shows that the vein has not formed by replacement, but has filled a fissure; and the concentric banding of some of these veins, growing from the walls toward the center, often with unfilled vugs in the center, shows that it is not crystalliza-

tion that has forced the walls apart, as has been contended by some.[16] To me, as I have elsewhere stated, the plain inference is that the vein material (vein magma) is injected into the rock fissure, just as a dike magma, which later becomes igneous rock, is injected; that it forces aside the walls by its own pressure, and then holds them till its crystallization or freezing; and that its specific gravity, or its viscosity, or its gaseous-tension pressure, or its motion, or all, frequently enable it to float or support angular fragments torn or floated from the walls. The question as to the origin of the fine rhythmic banding then becomes an interesting one, since it apparently results from a process of crystallization within the ore magma, building out from walls and inclusions: not so much by deposition of mingled metallic minerals and gangue, but first one and then the other, as if the precipitation of one band—say of metallic sulphides—left the magma unbalanced, with quartz in excess, and the resultant deposition of quartz left sulphides in excess, and so on, each deposition having a momentum which left the other material in excess. The frequently noted phenomenon of broader bands as the distance from the walls or inclusions increases may be due to a loss of density (through precipitation) in the magma solution; and the common occurrence of vugs in the center of such veins or portions of veins may well mean that the entire precipitation failed to fill the space occupied by the vein magma, and these vugs contained finally only residual water and gases. Such vugs occur, for example, in the finely banded later phase of the Montana Tonopah vein (Fig. 83). They are very small in relation to the size of the whole vein, and are lined with adularia crystals. The older portion of the vein, which is massive, and shows no banding, is of quartz, carrying disseminated silver sulphides; while the later, banded portion shows beautifully fine alternations of rich

[16] S. Taber: *Trans.* A. I. M. E., Sept., 1918, p. 1191; F. L. Stilwell, *Econ. Geol.,* Vol. XVI, No. 2, March, 1921, p. 158.

black silver sulphide layers with layers of quartz and earthy carbonates.

If the central vugs which are occasionally found represent or partly represent the excess of residual water and gases, we may infer that even in the case of this apparently relatively thin type of true ore magma the proportion of water is not excessive. In the phenomenon of minor central vugs, this type of mineral veins resembles some pegmatites, which, therefore, similarly show a certain shrinkage on crystallization. Such mineral veins accordingly represent the relatively watery or pegmatitic ore magma—but not the residual waters.

This phenomenon of successive rhythmic precipitation is one that is not unknown in igneous rock magmas. The "orbicular diorite," for example, shows a similar structure (Fig. 84).

Rhythmic and concentric banding of this kind was found by Liesegang in 1896 to occur in a gel or jelly. A drop of silver-nitrate solution was placed on a film of gelatine containing potassium bichromate. The resultant silver bichromate did not form a continuous zone or halo around the drop, but formed in concentric rings, separated by apparently clear spaces of increasing width. More recently Hatschek and Simon[17] conducted experiments on this reaction, using test tubes filled with silica gel or jelly, instead of the gelatine film. By the application of a reagent on top of the jelly, the precipitation in concentric rings took place in the jelly, or, under certain conditions, on its upper surface. This led to the surmise that banded veins such as we have under consideration were in the state of silica jelly when the banded precipitation took place.

A silica jelly contains about 14 per cent SiO_2. Such a proportion of silica is markedly greater than the 0.03 per cent of silica (11.41 per cent of 0.285 per cent) in the waters of Steamboat Springs, or the 0.05 per cent (45 per cent of 0.113 per cent) in the waters of the Grand Geyser of Ice-

[17] E. Hatschek and E. Simon: *Trans.* I. M. M., Vol. XXI, 1912, p. 452.

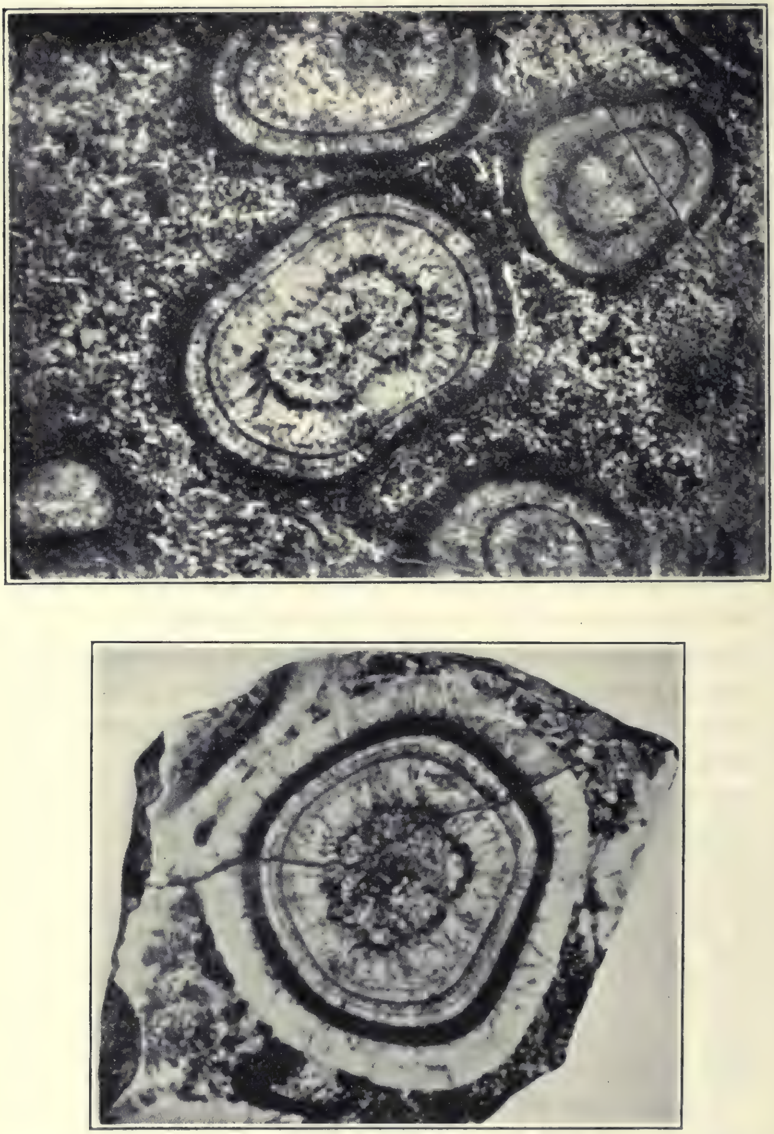


FIG. 84.—Orbicular diorite. Showing fine banding in crystallization of diorite magma, due probably to rhythmic or pulsating deposition of crystalline substance from the fluid magma. After James Geikie: "Structural and Field Geology," 1920; Plate XIV.

land, which seem to represent the relatively highly siliceous hot-spring waters: indeed, it is several hundred times greater, and more nearly approximates my conception of the ore magmas as outlined in Chapter II. In this chapter, however, I state my belief that the amount of water might even be less, say in some cases 50 per cent. As I have in various places throughout these essays indicated, there appear to be various kinds of ore magmas, some relatively dry and aplitic, some relatively aqueous and pegmatitic; and the residue of each on consolidation would appear to be water —"mineral" water, the nature and effects of which must not be confused with the ore magma. The more aqueous vein magmas, whether siliceous or metallic, have the power to pass through small interstices of rock, and so impregnate and replace it, a property which it is clear any solution might accomplish, and indeed a saturated solution more thoroughly and quickly than a watery one. On the other hand, there appear to be vein magmas, such as that I have described at Santa Eulalia (p. 322) and others (see p. 716), which are too dry to do this, and are confined to the fissure along which they intrude, almost as strictly as are igneous rock magmas. The quartz veins of California, which, according to descriptions, are like those of Australia,[18] seem to be of this type, for they do not penetrate the wall rock, in which the alteration is to iron carbonate. These quartz veins, like all the characteristic gold-quartz veins of the deep zone, allied to the pegmatites (gold-bearing pegmatites are reported from Australia),[19] are massive and without structure, and the vein magma from which they crystallized certainly cannot have been especially aqueous. The carbonate in the silica magma, which in many instances precipitated, before the crystallizing of this magma, as a thin film on the walls and around inclusions, was probably also contained in the residual waters.

[18] N. R. JUNNER: "The Geology of the Gold Occurrences of Victoria, Australia," *Econ. Geol.*, Vol. XVI, No. 2, March, 1921, p. 79.

[19] *Op. cit.*, p. 92.

I have above mentioned that the finely banded portions of quartz-metallic-sulphide veins like the Montana Tonopah, which are later than the main massive portion of the veins, and appear to have been possibly more jelly-like and aqueous, are also richer than the main vein. I believe we have here something very like a universal law, which we will do well to consider attentively. I believe that we are to consider a common type of vein magma—at all zones from the pegmatitic zone up to the silver zone—as essentially, like the pegmatitic magma, a fluid silica magma containing dissolved metals and metallic sulphides, and kept fluid at relatively low temperatures by water and other gaseous constituents. Upon the stiffening and final consolidation of such a siliceous vein magma, under proper temperature-pressure conditions, to form a quartz vein, I believe a constant tendency may be observed toward a simple form of fractional crystallization or magmatic differentiation (see Chapter II), in that the silica tends to crystallize first, the metallic sulphides and the native metal (gold) subsequently, or at least to separate out and crystallize independently. This sequence is in most cases a gradual one, and not clean-cut, showing by this very fact that we have here to do with an internal segregation in a single magma, and not (typically) with two distinct periods of deposition, or independent solutions. In the quartz of the main body of such veins, intimately disseminated and of contemporaneous crystallization, a certain amount of these sulphides (and gold) will be found; but the later crystallization, more scanty in quantity, will be found to be richer in the metallic minerals, with less gangue, or even practically without it.

This law of the later crystallization of the metallic minerals explains not only the later banded and richer ores like those in the Montana Tonopah instance; it explains the phenomenon of the MacNamara vein in the MacNamara mine, at Tonopah (p. 153), where the pay-ore is mainly an impregnation in the hanging-wall country rock of the main

quartz vein, here too low grade to mine. It explains the occurrence of rich sulphides and free gold in fractures in the main and earlier quartz veins of the Mother Lode in California, and impregnating the wall rock; and also the similar occurrence of gold and arsenopyrite in crevices in the earlier quartz veins and in the wall rock at Herb Lake, in Manitoba (p. 106). In many districts this law may be observed, as in the El Oro district in Mexico, where the main quartz lodes are of large size and low grade, and the presumably later ones are narrower, frequently finely banded, and high grade (Chapter VIII, p. 366); or the high-grade sulphides may occur along a wall of the main quartz lode, or even as a richer subsequent or practically contemporaneous streak within it. The gold-quartz veins of the Appalachian belt in the eastern United States show similar characteristics; and thus the same law is shown for the deep-seated quartz lodes and those of the upper zones. In many of these cases the two stages of precipitation—of earlier low-grade quartz and later high-grade sulphides (and gold)—are strictly confined to a single vein or lode, showing that the phenomena represent the stages of crystallization of a single fissure-filling of siliceous vein magma. In other cases, as at El Oro and elsewhere, the later stages sometimes acquire independence enough to occur in individual fissures, but near the parent one, as well as in streaks within the earlier veins; and these are the rich small "auxiliary" or "subsidiary" veins with which we are all familiar.

By some such process of differentiation the important highly metallic vein magmas seem to have been formed, and such ore magmas become independent intrusives, and on a large scale.

The point always to keep in mind is that the silica is the companion of the ore, but is not the ore; that the two are companions because both are end products of magmatic differentiation; but that they tend to dissociate themselves. Therefore, the sequence of ore deposition has to do with

the sequence of metals, with or without accompanying quartz gangue. The subsidiary gangues of these siliceous veins, other than quartz (calcite, magnesium, iron and manganese carbonates, barite, fluorite, etc.), are to be conceived of as parts of the same typical siliceous vein magma. They may crystallize in part with the quartz, but tend rather to be residual from its crystallization, therefore frequently to be closely associated, as gangue, or as associated but subsequent barren veins, with the metallic minerals separated from the crystallized siliceous vein magma and afterward crystallized.

Such earthy-mineral veins are to be regarded as differentiates from the siliceous vein magma, just as are the veins of solid sulphides.

Reverting to my main theme, my conclusion is that hot springs are not the solutions which accomplish ore deposition in general; and that the solutions which do this are far more highly concentrated, typically siliceous[20] vein magmas, from the final crystallization of which certain magmatic waters which rise to the surface are residual, in much the same way that such magmatic waters are residual (in vastly greater quantities) from the consolidation of a body of intrusive granite; and that these hot magmatic waters may permeate and modify the intruded rock, but have an effect and net result totally different from that of even the aqueous type of vein magmas.

As I see it, therefore, there are two great classes of ore deposits, or concentrations of the earth's elements, of commercial volume and purity—the one characteristic of the atmosphere-rock contact zone above the solid rock crust, and marked by quantitatively large concentrations of the commoner elements, chiefly through the precipitating effect of organic life; the other the result of the differentiation of igneous magmas in the zone below the solid rock crust, and marked by concentrations of all the elements, whether

[20] Except for the basic rock magmas. See Chapter XIII.

common or rare. Other forms of ore concentration I believe relatively unimportant.

I have dealt in this chapter hitherto with the formation of primary ore deposits, in which have been concentrated the elements from the normal scattered or disseminated condition in solid or molten rocks, in which they were diffused. There remains to be touched upon the important consideration of the action of the various fluids which we have discussed, upon these primary ore deposits, formed as above suggested. And we find that such secondary or subsequent action is very important. Ordinary surface waters, for example, which I believe quite unimportant as to drawing primary ore deposits from the original disseminated condition in the rocks, actively rework metallic deposits, including those due to magmatic action. This activity is again confined to the atmosphere-rock contact zone, and the chemical reactions are those set up by this contact.

The zone of oxidation in primary ore deposits is that zone where surface waters, bearing oxygen, thereby possess the faculty of breaking up old mineral combinations, taking metallic and other salts in solution, and precipitating them again, forming new mineral combinations and new metallic concentrations. An entirely different set of chemical reactions and laws here obtains, of course, from that which obtains in magmatic solutions. Since the surface waters ordinarily sink into the rocks, the tendency is continually to transfer the metals downward, and thereby to concentrate them and produce deposits of greater richness, especially as erosion wears the surface downward. The depth of the zone in which oxidizing waters have ordinarily been very effective of course varies locally. In regions which have been covered by the continental ice sheet there is usually little or nothing of this. Thus we are aware that the process is one that has taken enormous time, since the ice sheet disappeared some 100,000 years ago, more or less.

In non-glaciated countries the amount of precipitation is an important factor, for this determines the amount of the

active reagents and of their circulation.[21] Abundant rainfall keeps the crevices and fissures in the rocks pretty well filled up, so that it constitutes a sort of underground lake with an actual surface, for the downward and lateral flow is not free, even through this shattered superficial rock zone. Oxidizing waters cannot penetrate very far below the surface of this lake, which is not level, but follows to some extent the line of the surface, although, of course, not regularly: hence, the zone of active oxidation is thus limited to a restricted zone near the surface. Where there is less rainfall, as in arid regions, the ground-water level, as the surface of this lake is called, may lie much deeper, may be irregular or ill-defined, or may, indeed, not exist at all, and oxidizing waters may there sink deeply, and the zone of oxidation penetrate downward for hundreds of feet.[22]

[21] In the case of the Mandy mine, in Manitoba, there has been no oxidation or even secondary sulphide alteration of the primary sulphide ore since the period of continental glaciation, a lapse of many thousand years. Unaltered primary sulphides were revealed when the protecting moss was pulled away. The fact that relatively slight oxidation is characteristic of the whole region that underlay the continental ice sheet, while profound alteration and the development of secondary sulphides characterizes the ores which lay south of it, inclines us to believe that on the whole the superficial alteration of ores by surface waters, entailing oxidation and secondary sulphides, has been a very slow process; and that those which show great effects of the sort have been outcropping for a very long time, by our standards. The "porphyry copper," or great bodies of secondary copper sulphides, all lie south of the limit of glaciation, and the same is true of important deposits of oxidized ores. As the lapse of time since the glacial period is estimated at from 50,000 to 100,000 years, we must concede that the deep oxidation zones at Butte, Leadville, and elsewhere have taken many times that period to form, or from one million to several million years.

[22] In certain cases zones of oxidation, accomplished in earlier ages, many millions of years ago, have been covered up by later rooks, and when opened up by recent erosion are shown to have changed character but little. For example, the oxidation processes which have concentrated, from the original silicate, the iron oxide ores of the Mesabi, are believed by Leith to have been practically entirely pre-Cambrian. And, similarly, in Arizona some of the copper deposits show deep zones of oxidation attained at some ancient epoch, and preserved, by burial under subsequent rocks, to the present day. Such, for example, is the case at Jerome, according to Ransome and others.

The ease with which metals are thus moved downward by the oxidizing surface waters also depends on the metal. Gold, for example, is relatively insoluble; hence it is not carried far beneath the outcrop, and the outcrop and the shattered rock immediately beneath become enriched by the gold which accumulates in it, partly mechanically, as the vein wears down. Outcrops are also frequently rich in silver, particularly in arid regions, where the enriched mineral may be chiefly in the form of the relatively insoluble chloride, a secondary or subsequent combination, the original or primary form as deposited being sulphide. It is likely that the relatively scanty and, therefore, alkaline ground waters of the desert regions determine the chloride form.

Copper, on the other hand, is easily dissolved by descending waters, and the outcrop is generally partially, and sometimes entirely, leached of copper, leaving, from the oxidation of the pyrite which accompanies the copper, or from the iron of copper pyrite, a mass of iron oxide at the cropping of the vein, which is sometimes called "gossan."

Such leached copper is carried down to the zone of unoxidized primary sulphide ore, and is there precipitated as sulphides, usually much richer in copper than the primary sulphides. Cupriferous pyrite, which may be quite poor in copper, is thereby enriched to chalcopyrite, or more characteristically to chalcocite, while other secondary rich sulphides, such as bornite, are common. This process is very important in the preparation (genesis) of commercial copper ores, and many a copper deposit does not pay commercially, and cannot be worked as ore, after the primary sulphides have been reached in depth. Incomplete leaching in the oxidized zone may result in considerable copper carbonates or oxides; or, due to an approach of the rich secondary sulphide zone to the surface, through erosion which is more rapid than the downward migration through the agency of descending waters, the rich sulphides may become par-

tially oxidized into rich carbonates and oxides, as in the Rosita mine, which I opened up in Nicaragua.

Of vast commercial importance in the class of secondary sulphide copper ores are the disseminated copper ores, known colloquially as the "porphyry coppers." In the semi-arid, non-glaciated region of Western North America, in Utah, Arizona, Nevada, New Mexico, and Mexico, there are deposits of lean cupriferous pyrite thinly disseminated in some igneous rock (usually monzonite), or in schist. Under favorable conditions the copper of these deposits, which do not constitute commercial ore, since they usually assay much less than 1 per cent copper, is several times enriched,

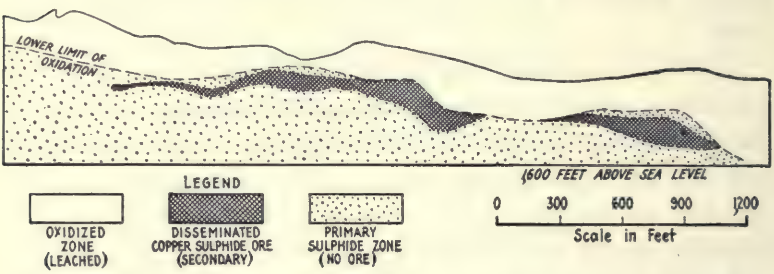


FIG. 85.—Ray, Arizona. Vertical section showing bodies of secondary sulphide ore and their relation to the primary lean sulphides and to the oxidized and leached zone. Part of Section B, Fig. 50.

so that in the secondary sulphide zone, which lies between the barren leached zone next the surface and the primary disseminations below, the ore runs from 1 to 2 per cent and sometimes more. Such an enriched zone may be up to a few hundred feet thick, and constitutes a blanket lying parallel to the surface, and frequently amounting to many millions, and even hundreds of millions, of tons of low-grade ore. Of these deposits, I have made a study of the ore at Ray, Arizona (Fig. 85); and I should like to describe some of the interesting peculiarities of this important type of copper ore, but the type is fairly well understood, so for our purposes may be briefly passed over. These ores are mined sometimes by stripping off the barren

leached surface zone by steam shovels, as at the Utah Copper mine, and then mining the ore in the same way. Where the leached zone is thicker, underground methods of mining are resorted to, as at Ray.

Such disseminated secondary sulphide deposits are found only in the case of copper. Similar primary disseminated deposits are of gold-bearing pyrite: I have examined several which contain many millions of tons, but on account of the insolubility of the gold there is little or no zone of sulphide enrichment, with the result that most of these primary deposits have not yet been found to be workable. Practically of this type, however, are the great low-grade deposits near Juneau, Alaska—the Alaska Juneau and Alaska Gastineau, with ore averaging perhaps around or below $1, which so far has proved of too low grade for profit.

The idea of "secondary sulphide enrichment" threw so much light on the processes which go to make up merchantable copper ores, that it has been eagerly sought to apply it widely. Many writers describe a secondary sulphide zone in gold ores. I have not seen any. Argentiferous galena undergoes a secondary sulphide enrichment, the enriched sulphides often coating or reticulating the original less argentiferous galena. Such secondary ores are characteristically finer grained (less coarsely crystalline) than the primary ores: the larger content of silver seems to interfere with the free crystallization of the galena.

The concentration of galena by descending surface waters is illustrated in Fig. 86, showing observations I made in Monte Cristo, Washington. The primary ore is arsenopyrite, pyrite, pyrrhotite, chalcopyrite, and some blende, carrying gold, and showing lead only on analysis; but close to the surface (this is a region of very heavy rainfall) galena occurs in the vein, and its lower limit follows the contour of the surface. There is little oxidation here, and the sulphides generally outcrop.

Silver is also deposited in concentrated sulphide form by descending waters, in the form, especially, of argentite.

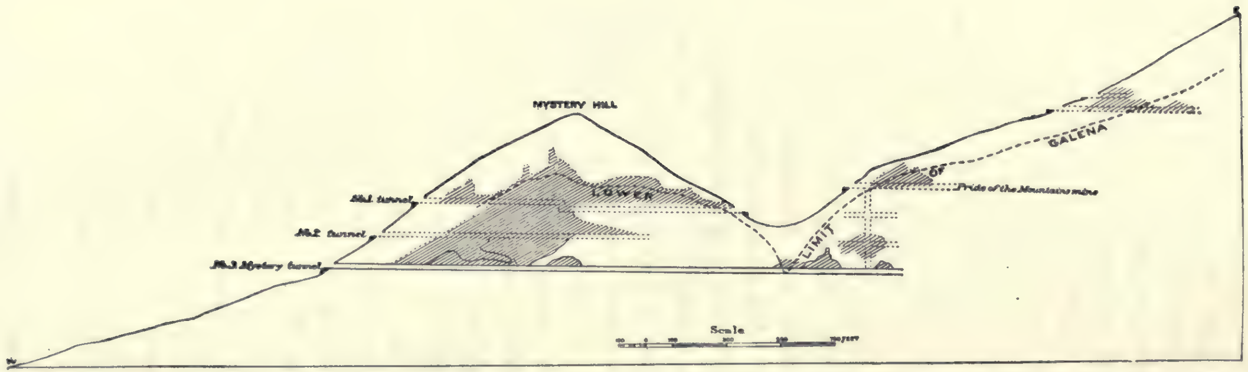


FIG. 86.—Mystery-Pride vein, Monte Cristo district, Cascade Mountains, Washington. Longitudinal vertical section. Shows galena formed near the surface by surface waters, through alteration of a mixed sulphide ore (arsenopyrite, pyrite, chalcopyrite, blende, and a little lead). Shaded portions are developed bodies of pay-ore. Region of heavy rainfall; practically no oxidized zone. By J. E. Spurr: Twenty-second Annual Report, U. S. Geol. Surv.; Fig. 119, p. 841.

Silver sulphantimonides and sulpharsenides, combined often with copper and other bases, such as ruby silver (pyrargyrite and proustite), argentiferous "gray copper" (tetrahedrite), tennantite, polybasite, and similar rich silver minerals, were formerly considered by most of us as clearly due to downward secondary sulphide enrichment by surface waters, quite in the way that chalcocite is formed from cupriferous pyrite. The doubt about this whole matter is decreasing: I have shown that at Aspen the phenomenally rich silver sulphantimonide (polybasite) is primary,[23] and is even earlier than the argentiferous galena, from which some writers assumed that it had been concentrated by downward-moving waters. At Tonopah I found that nearly all of the rich silver sulphides, including polybasite, stephanite, and argentite, are plainly primary; and E. S. Bastin later checked the correctness of this by metallographic studies. Dr. Bastin subsequently demonstrated the principally primary origin of the similar rich silver sulphides of the Comstock lode.

At Aspen the rich silver sulphides have become reduced to native silver, mainly by a combination of descending waters and the reducing action of carbonaceous shale; and at Tonopah I found reason to believe that the scanty ruby silver and also some of the argentite was secondary, and due to descending waters. Altogether, and running over the matter in my mind, I am inclined to doubt whether we find secondary silver sulphantimonides and sulpharsenides like polybasite, tetrahedrite, tennantite, and stephanite except where there have been primary minerals of the same type; and that perhaps most occurrences of these minerals, which have been assumed to be secondary, are primary. What has fooled geologists is the characteristic occurrence of these rich silver sulphides in a stage of primary ore deposition distinct from the argentiferous galena and other metallic minerals, and generally a later stage, so that the silver minerals cut the galena as they might if derived from it. On the other hand, ruby silver seems to be an

[23] *Econ. Geol.,* Vol. IV, No. 4, p. 314.

antimonial or arsenical silver sulphide compound which is mainly secondary, and some argentite seems certainly secondary, though some also is primary; but it is doubtful if even secondary ruby silver occurs except as a reworking of primary silver sulphantimonides and sulpharsenides.

Although lead and to a less extent zinc are concentrated by descending surface waters as secondary sulphides, they are concentrated in a far more important way in the oxidized zone. The primary ores are often mixtures of argentiferous galena and zinc-blende. Under the disintegrating and dissolving effects of surface-derived waters, such an ore becomes reworked, by dissolution and subsequent deposition as carbonates. Thus the lead frequently becomes well separated from the zinc, as at Leadville and numerous other places. The mines of Northern Mexico furnish many examples. The zinc is characteristically carried lower down than the lead, and may be deposited sometimes in clear separate bodies. In some places the zinc replaces the wall rock. I have seen, for example, instances where the wall rock of a mixed original galena-blende-pyrite orebody was limestone (as at the Zaragoza mine, near Monterey, Mexico). The lead, in the form of mixed secondary galena and lead carbonate, mingled with iron oxide derived from the original pyrite, remained in nearly or quite its original position, but much of the zinc had been carried into the wall rock, and replaced the lime carbonate by zinc carbonate (smithsonite), so that it became a commercial ore, while the texture, structure, and much of the color of the limestone was retained. Thus the lead ore was stoped up to this supposed limestone wall, with no suspicion that the wall was zinc. This "camouflaging" of the secondary zinc carbonates, which have replaced limestone, is very common; and when the secret was out, it resulted in reopening many of these old Mexican lead mines, and discovering unsuspected zinc ores which had been opened up and left; and later much the same series of events followed at Leadville.

In this dissociation of lead and zinc by oxidizing waters (carrying carbonic acid), the silver goes with the lead and not with the zinc. To a certain extent, however, it may be dissociated from both, and as in the case of the zinc carbonate above described, carried out into the limestone wall rock and there precipitated. At Santa Eulalia, Mexico, for example, in the Mina Vieja, I have observed that the limestone wall rock in the vicinity of the oxidized orebodies has been impregnated with sufficient silver to make it a silver ore, but it does not contain lead or zinc. This limestone has been rendered pinkish by manganese, which recalls Dr. W. H. Emmons' theory that manganese solutions are the chief carriers of silver under such circumstances.

In the case of persistent and deep-reaching fissure veins which undergo enrichment by descending waters, whether in the oxidized zone or in the sulphide zone, or both, as erosion progresses: if the downward leaching keeps ahead of the wearing down, so that the enriched ore is not robbed from the vein by erosion, the enriched elements in the vein may be repeatedly concentrated. In some cases this downward enrichment, especially where the vein is open and is a natural water-course on account of fissuring subsequent to the primary mineralization, may migrate quite down to the bottom of the original orebody, or even past it, following down the barren vein fissure, so that the whole of the ore is secondary. I have described this condition for a group of veins in the Georgetown district, Colorado.[24]

Altogether, while I do not believe that the concentration of the disseminated rarer metals in the rocks by descending surface waters is of any importance whatever (except occasionally at and just below the surface, as residual deposits), the effects of these waters on ore deposits formed by magmatic ore solutions, in enriching them, are of enormous commercial importance, and this enriched ore forms one of our chief supplies.

The fact that even these primary ore deposits do not yield

[24] *Professional Paper* 63, U. S. Geol. Surv., 1908, p. 144.

to the concentrating action of ground water (of atmospheric origin) far below the zone of oxidation—that is, not below the zone of sulphide enrichment which is a part of the atmospheric reaction-zone—and that the primary ores beneath are found absolutely unmodified, is in effect a demonstration of my conclusion of the inability of deep ground waters to form primary ore deposits. If they can do nothing with an already completed concentration of metallic minerals, toward dissolving and reprecipitating them in more concentrated form, why should we assume that they could bring about intense and highly localized concentration from disseminations a hundred thousand times more thin? It is not that they have not had plenty of time—the time has been ample for any and every geologic phenomenon. Since pre-Cambrian, or Permian, or Jurassic, or Cretaceous, or Middle Tertiary time, as the case may be, these deep ground waters have had a chance to see what they can do with these primary magmatic metallic concentrations, and the result of the test is everywhere conclusive—they can do nothing. They are inert, and the primary ore deposits are practically immutable from the time of their swift formation down to the time when erosion brings them near enough to the surface so that they come within the thin atmosphere-ore reaction-zone; and then, within this zone, the effects of the air and water are wonderfully destructive and constructive, as I have described.

Downward solution and deposition, bringing about downward migration of the metals in a vein, must, of course, work more swiftly than erosion if the accumulated store is to survive being wiped out. The fact that continental glaciation has wiped it out shows how much more rapid and trenchant was this glacial erosion than are normal erosion processes. Under ordinary conditions the downward migration of minerals is a swifter process than erosion, even in mountainous and rainy regions where wearing away is swiftest; but in certain of the latter erosion is as swift.

The enriching effect of downward-moving surface waters

has been sketched. A few words should be said concerning what occurs under certain conditions—shallow surface waters moving upward, and back to the surface. This is characteristic of hot, dry regions, where the surface heat produces a flow—probably chiefly capillary—of the moisture in the rocks to the surface, where it evaporates, depositing its solid constituents. The best-known and economically most important deposits are the playa salts of Nevada and California. Playas ("dry lakes" or "alkali flats") are smooth floors of hardened silt in the bottoms of depressions where lakes would be in moister climates. Occasional rains do stand on top of these deposits as a shallow sheet for a while, and then sink in. Under the influence of the desert sun they return to the surface, leaving there a white crust, which in different places contains salt, soda, or borax. These superficial, salt-impregnated upper layers may be scraped up and leached; and some of these deposits have been of commercial value in the past.

The nitrate deposits of Southern California have a similar genesis.[25]

This process operates to enrich outcrops in the desert, and even to enrich faces of ore in mines which have been left standing a number of years. Experienced samplers are aware of this, and are careful to clean off the outside of a face before sampling.[26] Miners, who frequently note this phenomenon, are prone to construct extreme theories of ore deposition therefrom. This process is most active in porous ores. Even copper may be concentrated by this process. Examining a mine near Sodaville, Nevada, I found the ore to be cuprite impregnating a sandstone. The impregnation was richest at the surface, and continued down, diminishing for about six feet. Below that the copper

[25] L. F. Noble, G. R. Mansfield, and others, Bull. 724, U. S. Geol. Surv.

[26] I once nearly "salted" myself in examining a North Carolina disseminated gold deposit by not cleaning off deeply enough. The faces of old workings, to a depth of two or three inches, had thus been enriched, after standing since Civil War times, to about ten times the value of the virgin ore.

content diminished to 1 per cent, although this surface enrichment averaged 6 per cent for six feet down. It is likely that the rich outcrops of gold and silver veins in the arid region owe some of their values to these processes; and Dr. Penrose has informed me that he thinks it possible that the radium ores of Southern Colorado may be enriched in the surface crust in this way. At Inde, in Durango, Mexico, in the arid region, I found that the outcrops were silicified by this process; and the waters drawn thus to the surface also deposited silica along crevices, thus forming quartz veinlets, which in part are gold-bearing; but such veinlets are usually confined to within a few feet from the surface.

Finally, let us consider the effect of *ascending hot waters* (such as emerge as hot springs) on primary magmatic ore deposits. It is unnecessary to observe that these, by virtue of their heat, have far more power to dissolve and hence to precipitate and concentrate than the surface waters, the importance of whose work beneath the atmosphere-rock superficial contact zone I have denied. Further, waters partly or wholly of magmatic origin may well constitute the majority of hot springs. It is clear that many hot springs are of mixed origin, as I have shown, for example, in the frequent coupling of hot and cold springs in the arid Nevada region, within a short distance of each other. In general the cold springs of Nevada clearly show their atmospheric origin, since they fluctuate with the season, and increase in abundance in the regions of greater rainfall. The hot springs, however, do not show these features, but are notably associated with areas of volcanic rocks and, therefore, seem to be essentially deep-seated and probably magmatic. The coupling of hot and cold springs, therefore, shows that waters of diverse origin are ascending along the same fracture zone, and are kept from mingling only by some impervious barrier of gouge or decomposed rock. At Silver Peak, in Nevada,[27] a spring of nearly scalding water

[27] J. E. Spurr: *Professional Paper* 42, U. S. Geol. Surv., p. 256.

and one of at most lukewarm water rise within a score of feet of each other. A primitive bath house stood between the two in the days of my visits there, and the bather dipped the waters with a bucket into a tub, and cooled off those of the hot spring to the desired temperature with the other. This is far from an isolated example. Such waters of diverse origin must, of course, in many cases mingle before emerging.

Comparing the potency of the atmospheric waters with those of hot springs, it is unquestionable that the magma-derived waters contain active reagents which may perhaps partly take the place of the oxygen, carbonic acid, and derived soluble salts which make the atmospheric waters so potent close to the surface of the earth. Such magmatic waters do not contain oxygen, but they do contain carbonic acid, and, indeed, frequently much more powerful reagents, like chlorine, free hydrochloric and sulphuric acids and the like, as well as soluble salts which may react with substances which they encounter, far more actively than would cold solutions. Such hot solutions probably decompose and reduce the rocks along their channels, substituting new compounds for old, and frequently bringing about a fairly widespread alteration of the rocks for some distance from their channels, through which they penetrate, along crevices, and, indeed, by capillary action, throughout the solid rock. In their work they are under this comparative disadvantage as compared with the atmospheric waters, that the latter fall on the earth free from minerals in solution, purified by that distillation process which is peculiar to the earth's surface; while magmatic waters, from beginning to end, must be heavily laden. On the other hand, some of the materials which they carry may have been derived directly from the magma, as in the case of cinnabar, above discussed, and probably of other materials, especially the earthy salts; and the amount of these materials which they can carry in their heated condition may bring about under favorable conditions considerable precipitation of certain

vein-stuffs, especially silica, aluminum compounds, and lime. Nevertheless, on account of the clear distinction which there seems to be between the typical hot-spring waters and the ore magmas which appear to have formed most veins, I am inclined, as I have explained above, to assign a minimum rôle in ore deposition to this final magmatic end product, hot-spring waters, and then only regard it as a factor in ore deposition mainly through the persistent magma-derived elements, like mercury, which it may still contain, and drop from solution; and not through its action in searching out and concentrating small quantities of metals from ordinary rocks, igneous or sedimentary, a process which I am inclined to minimize as occurring on a scale of importance, or as resulting in any of the deposits which we regard properly as ore deposits.

But, as in the case of the atmospheric waters, the action of ascending hot waters on already formed magmatic ore deposits is quite a different problem; and it is logically altogether likely that in such cases considerable solution and redeposition, and even concentration, may be effected thereby, but probably in a vastly less important degree than in the case of surface waters. And this logical conclusion is borne out by certain phenomena which we find in ore deposits of magmatic origin, indicating, subsequent to the main formation, later and minor deposition along fractures and in vugs, which suggest the work of magmatic waters of the hot-spring type.

Veins have a tendency to remain natural circulation channels, even after they are formed, for they remain zones of weakness, and subsequent strains in the rocks tend to create new fissures along them. Hence atmospheric waters are often tapped when veins are cut in mining operations; and, naturally, it sometimes occurs that hot-spring waters seek the same channel, as in the case of the Comstock.

In the case of the White Caps mine, at Manhattan, Nevada, as described by Ferguson,[28] there is recorded what

[28] *Econ. Geol.*, Vol. XVI, No. 1, Jan., 1921, p. 28.

appears to be a case of a two-agency ore deposit, to which I have before referred. The first deposition was of quartz, arsenopyrite, pyrite, and gold, with fluorite and leverrierite (a hydrous silicate of aluminum, resembling sericite); and at a later date came the deposition of stibnite, and according to Ferguson probably the alteration of auriferous arsenopyrite to realgar, which remains auriferous. The realgar is found to the lowest level explored (800 feet), and Ferguson suggests that the solutions of this second period were ascending. As I have previously pointed out, some cinnabar appears to have been deposited, probably also at this later period, so that the results altogether are those which might have been performed by the most active type of magmatic hot springs (like Steamboat Springs, in Nevada). There was, however, no particular enrichment, or concentration of gold, connected with this alteration of arsenopyrite to realgar; nor does the arsenic and the gold appear to have been carried far. The net result appears to have been that the hot ascending waters carried away the iron (from the arsenopyrite) in solution.

Realgar is commonly observed as a secondary sulphide after arsenopyrite. I have described an instance of the alteration of arsenopyrite to realgar at Monte Cristo, in Washington.[29] Realgar has formed in this district in cracks in older auriferous arsenopyrite. I considered this the work of descending surface waters. The fact, however, that in this district it is contemporaneous with stibnite, and that these two, with calcite, are later than all the other sulphides, forms such a strong resemblance to the Manhattan occurrence as to suggest that at Monte Cristo also the alteration was the work of ascending hot waters, the last phenomenon of magmatic ore deposition.

Both at Manhattan and at Mercur (Utah) the deposition of auriferous realgar, cinnabar, and stibnite was accompanied by little if any deposition of gangue material. At Mercur no arsenopyrite has been found. The characteristic

[29] J. E. Spurr: *Twenty-second Ann. Rep.*, U. S. Geol. Surv., p. 837.

ore at Mercur is accompanied by a disintegration and rendering soft and often pulverulent of the rocks, whether limestone or porphyry; and the mineralization is connected with open fissures which are later than an earlier flat ledge (vein) of quartz with barite and carrying some silver, probably originally in the form of a sulphantimonide of silver and copper. Realgar is sometimes found coating the open fissures. On account of the conspicuous lack of gangue in the gold ores of the later period, and the association, with the gold, of arsenic and mercury, I advanced the hypothesis that they were deposited from solutions which were in a gaseous rather than a liquid condition.

The symptoms at Manhattan are similar. I noted there auriferous realgar and cinnabar deposited in a soft black disintegrated material like fault gouge, which contained angular fragments of wall rock and of earlier calcite vein material. Both of these similar cases certainly constitute exceptions to the more usual rule of ore deposition, in that the mineralizing agents did not silicify or cement the rock traversed, but softened and disintegrated it, depositing the arsenic and mercury sulphides in the interstices and coating fractures.

The apparent instability of arsenopyrite in hot-spring waters, and its alteration by them to realgar, appears to be an indication which should be carefully considered. Realgar has been found in the deposits of hot springs, but I have not seen arsenopyrite thus described; similarly, realgar has been found in the deposits from the fumaroles of volcanoes, but not, so far as I know, arsenopyrite. Here is an associated trio—ore deposits like those of Manhattan, hot springs, fumaroles—which is evidently significant. Realgar is unknown as a primary mineral in ore deposits in general, although arsenic in the form of arsenopyrite, or, more rarely, in other forms, is very common. The failure to find the ordinary form of arsenopyrite around volcanic fumaroles can hardly be ascribed to low temperature, for many of these fumaroles are very hot, as is shown by the

occurrence around them of minerals like specular hematite, pyrrhotite, and compounds of tin and molybdenum.

Realgar may be found to considerable depths. At Manhattan it is found to the lowest depths of the mine—770 feet—and allowing for erosion we see that it must have been deposited at least down to depths of 1,000 to 2,000 feet. In the Monte Cristo district I noted it down to at least 1,000 feet below the surface. Stibnite is frequently contemporaneous with realgar, as at Manhattan. Some stibnite veins carry arsenopyrite, such as some of those in Nevada, while others carry realgar, such as those in Tuscany.[30] Both carry cinnabar. The problem is one that requires further investigation: but, altogether, the collected evidence makes it look as if the hypothesis that the realgar at Manhattan and Monte Cristo had been deposited by ascending hot-spring waters, as an alteration of arsenopyrite, was a good one to hold in mind. At Mercur, the realgar (and cinnabar and gold) have certainly been deposited by ascending agents, as the position of the ore on the lower side of a sheet of intensely decomposed porphyry shows. But there is no evidence in this district that the realgar was derived from arsenopyrite, of which no trace exists. Disseminated fine pyrite occurs in these ores, but is not associated with the realgar, and was held to be the result of the transformation of the iron in the original rock to sulphides at the time of the mineralization. Under these circumstances the failure to form arsenopyrite is striking; especially as at Manhattan also some pyrite is contemporaneous with the realgar.[31]

In the crater of Vulcano[32] ferric chloride has been deposited with the realgar. Iron occurs in some hot-spring and solfataric waters, up to several per cent, although there is only a trace in the waters of Steamboat Springs. The

[30] W. Lindgren: "Mineral Deposits," Second Ed., 1919, p. 502-3.

[31] H. G. Ferguson: *Econ. Geol.*, Vol. XVI, No. 1, Jan., 1921, p. 25.

[32] A. W. Grabau: "Principles of Salt Deposition." McGraw-Hill Book Co., 1921, p. 341.

formation of primary realgar (instead of arsenopyrite) by ascending solutions, then, appears not to be due to lack of iron, but to the nature of the solutions. As to that, I have already expressed the opinion that the typical ore magma, from which, for example, arsenopyrite deposits are crystallized, is a much more concentrated solution and is much less aqueous than the hot-spring magmatic waters which have deposited cinnabar, realgar, and probably stibnite; and, probably, arsenopyrite was deposited at far greater (perhaps principally gaseous-tension) pressure.

We may fall back on the hypothesis that hot waters and gases are residual from the crystallization of magma at any stage, whether it be rock magma or ore magma; and that where they are from the crystallization of ore magma they carry the metals which are volatile at the lowest temperatures—namely, mercury, arsenic, and antimony.

The relative problem of stibnite (pure antimony sulphide) deposited from these hot-spring waters, as compared with the combinations of antimony with copper and lead—like tetrahedrite and jamesonite—in usually (but not always) deeper deposits which are plainly due to typical ore magmas, may constitute a case similar to the relation between realgar and arsenopyrite.

According to this, the presence of mercury, arsenic, and antimony in hot springs, and in this simple sulphide type of ore deposition in mines, indicates the precedent or accompanying formation of a more usual and normal type of ore deposit at greater depth, pressure, and temperature.

During the early stages of post-volcanic surface cooling, ore deposits of the usual type are apparently formed close to the surface, as in Tonopah and many other places which have been studied, and their nearness to the surface at the time of deposition may be approximately estimated. Silver and gold, separate or combined, are the most conspicuous metals in these deposits, but we also get, as I have noted in an earlier chapter, often in considerable quantity, sulphides of lead, zinc, and copper, and even veins of tungsten,

tin, and molybdenum. The high and variable temperatures which existed, at this stage, close to the surface, are thus shown.

Such deposits as the veins of Tonopah, which seem, at the levels where they are now disclosed, to have been formed a thousand feet or so from the surface, have often strong outcrops; that is, they once extended strongly upward past their present tops. How close to the surface did they get; and did not some of them reach the surface? Other forms of magma—rock magma—do reach the surface, as volcanic rocks, and have been traced (when dissected by erosion) from textural surface types (such as basalt and andesite) down to the granular types which are due to depth, and consequent greater slowness in loss of heat, in increasing viscosity and in crystallization.[33]

In the case of granites similar transitions are to be found. The cases I have noted and described are of biotite granite porphyry and biotite granite, transitional from biotite rhyolite. It is likely that biotite-muscovite granite, and muscovite granite, are more truly characteristic of greater depths, and form in the presence of more confined chlorine and fluorine.[34] Pegmatites, of course, are found only in association with coarse granular rocks, especially granites, and the same is true of pegmatitic quartz veins; though I have very tentatively suggested the possibility that the quartz-adularia veins may be the shallow-zone textural equivalent of the pegmatites, as the rhyolites are of the granites.

Ore magmas are apparently of plutonic origin, and some, like those of tungsten and tin, occur mainly in depth and in connection with igneous rocks having the corresponding textural characteristics; but with elevated temperature close to the surface, such tungsten and tin ore magmas may crystallize in the shallow zone, in the rhyolites or andesites, instead of in depth in the granites. There is no sound reason for thinking the temperature of consolidation of

[33] J. E. Spurr: *Jour. Geol.*, Vol. IX, No. 7, 1901, p. 586.
[34] *Op. cit.*, p. 594.

these superficial tin or tungsten veins less than that of the deep-seated tin and tungsten veins; but, in the former case, the congealing of the ore magma will have been more rapid, for the temperature is not so long sustained.

The occurrence of compounds of tin and other metals (cobalt, zinc, bismuth, lead, iron, arsenic, and copper) in the sublimates from the fumaroles in the crater of Vulcano, shows that these metals are deposited by the escaping gases. The gases include water vapor, carbonic acid, oxygen, nitrogen, sulphur dioxide, and hydrochloric acid, and also hydrofluoric acid; the precipitates, besides the metallic compounds above mentioned, include boric acid, iron, ammonium, and sodium chlorides; lithium and sodium sulphates; hydrous sulphate of aluminum and potash (potash alum); and the fluoride of silicon and potash (hieratite), with other minerals containing fluorine. As compared with veins, these products of volcanic sublimation are noticeably lacking in the earthy-gangue minerals, *such as quartz and the carbonates.* The products formed, including the metals, evidently have been brought in a gaseous form or in solution in gases,[35] and thus are contrasted to many of the vein deposits formed beneath the surface, the abundant silica and carbonate gangue of which stamps them as having been formed from more or less aqueous solutions or ore magmas. Metalliferous quartz veins, or metalliferous quartz-carbonate veins, do not come to the surface: none are reported from the cooled surfaces of any recent volcanic center. Between the fumarolic deposits of the surface, therefore, and the vein deposits formed at a certain shallow depth, there is a marked distinction.

Let us note that the metals, and boric acid, are described only from certain volcanoes; and that other volcanoes investigated show none· At Mont Pelée were found only

[35] At Katmai, in Alaska, zinc, copper, and molybdenum are found in fumarole products; they are surmised by Allen (*Journal of the Franklin Institute,* Jan., 1922, p. 51) to have come up in gaseous form, as halides (chlorides, bromides, or fluorides). The Katmai fumaroles are elsewhere listed as having temperatures of 95 to 414° (*Op. cit.,* p. 79).

ammonium chloride and sulphur, and sulphates of sodium, potassium, calcium, magnesium, and aluminum. No metallic sublimates are reported from the Hawaiian volcanoes, whose lava is basaltic. The amount of investigation performed is, of course, all too small, but it indicates the surmise that metallic precipitates, as well as boric acid, are formed only in connection with occasional volcanoes, *just as ore deposits are found only in association with occasional intrusive igneous rocks.* In other words, the gaseous and aqueous emanations from all lavas apparently do not contain appreciably the metals: the phenomenon appears, therefore, to be a special one, to be investigated discriminatingly.

I have earlier repeatedly pointed out that ore deposition took place at distinct and widely separated epochs (metallogenetic epochs); that at such epochs there were three allied processes—magmatic migration, crustal deformation (faulting and folding), and ore deposition. What about the present? Are ore deposits now being formed? Volcanoes are active in various parts of the world; so magma migration is going on. Certain earthquakes, and their associated fault phenomena, as in California, and evidence in mines, show that faulting is progressing, probably accompanied by folding. The lack of any greater evident catastrophic activity is an illuminating commentary on the relative slowness of magma migration and of folding and faulting, which slowness has already been reasoned out from the geological records of long-past similar epochs. As to ore deposits, it is to be inferred that they are being formed, since the phenomena allied to ore deposition are taking place.

One other important restriction governing ore deposition has been dwelt on: the metallographic province. And we can apparently only judge, therefore, where mineral veins are now being formed below the surface, from the character of sublimates of existing volcanoes, which, of course, is at the best only a very partial record indeed.

To study the problem further, we may investigate

slightly eroded volcanoes and volcanic necks. The great majority of these show no metallic deposits, although they may show evidence of magmatic waters. Others show ore deposits, which may be very rich. Cripple Creek is an example, where the present surface is estimated to be probably less than 1,500 feet below the original surface.[36] The rocks successively emitted by this volcano were: first, latite phonolite with syenite; next, phonolite; and finally basaltic dike rocks (trachydolerite, vogesite, and porphyritic olivine basalt—limburgite or monchiquite).[37] In this succession of types, all evidently derived from the same phonolitic magma, the process of differentiation is seen rapidly carried out, probably in obedience to a physical shift of the magma source to conditions favoring it. The mineralization was later than all of the volcanic rocks; was formed in fissures of little or no displacement, probably produced by adjustments of the neck after eruption; and consists chiefly of gold telluride, with pyrite, blende, and galena, some stibnite and tetrahedrite, molybdenite, and hübnerite (tungstate of manganese), and, rarely, chalcopyrite. The chief gangue minerals are quartz, fluorite, and dolomite, with celestite (strontium carbonate), orthoclase, roscoelite (vanadium mica), chalcedony, opal, rhodochrosite, calcite, and barite.

Clearly the Cripple Creek volcano, before any erosion, and soon after its eruption, was one of those unusual ones whose fumaroles would have been found, by the chemists of the Miocene period, if any had existed at that time, to be depositing metals; and, among the gases emitted, fluorine would have been prominent, as at Vulcano at present. But this phenomenon would only have been observed at a certain stage of the volcano's history—at the close of the volcanic activity and after its settling. The mineralization was a distinct magmatic episode, for numerous eruptions and intrusions occurred in the Cripple Creek volcano with-

[36] W. Lindgren: "Mineral Deposits," Second Ed., 1919, p. 476.

[37] Lindgren and Ransome: *Professional Paper* 54, U. S. Geol. Surv., 1906.

out being followed by ore deposition. Therefore, in the case of the metallic precipitates of the Vulcano crater, we may infer such a contemporaneous magmatic injection of metallic minerals below, now going on, or just achieved.

In the range of minerals at Cripple Creek I am inclined to see a considerable range of temperature during ore deposition. Some veins, for example, are of quartz, carrying galena and blende; yet there is no sharp line between these and the telluride veins.[38] The ores are regarded by Lindgren and Ransome as having been formed at depths varying from a few hundred feet to 3,000 feet. With such rich and varied ores formed within a few hundred feet of the surface, and the present outcrops in many cases still strong, it is difficult to see what prevented such solutions from appearing at the surface, and forming there, by the sudden precipitation, ores of unparalleled mass and richness, just as the hot spring builds up its sinter deposits around its orifice. The fact that none of the active or recent volcanoes or volcanic areas show any such phenomena leads to a strong hypothesis that the conditions of ore deposition are such that these surface deposits cannot occur. It is the more gaseous elements of the ore magma which reach the surface, carrying at best only a very small quantity of the elements which make up the metals and the gangue of mineral veins; where the ore deposition is deep, these gaseous elements, largely water, will be represented by hot springs, whose special content of boron, fluorine, etc., may mark their probable residual nature from the ore magma.

What are the physical conditions which prevent the ore magmas from overflowing on the surface, as the rock magmas so often do? It is hardly a question of temperature, for the volcanic fumaroles seem to be in part as hot as the temperature of ore deposition. Apparently, therefore, it is a matter of pressure, in that above a certain depth

[38] It has been held that orthoclase cannot form under a temperature less than 340° C. (see Chapter VI, p. 303, footnote). Orthoclase occurs in the Cripple Creek gangue.

the ore magma cannot retain its gaseous elements, which, therefore, dissociate themselves and escape, and thereby cause the disintegration of the ore magma, and the precipitation of the materials—metals and gangue—which are in solution: in other words, leaving the ore magma to crystallize as veins of quartz, earthy carbonates, etc., and the metals as sulphides and other compounds. When we consider this picture, we suspect that one of the chief agencies, at least, which holds silica in solution in the ore magma is hydrofluoric acid; and the sericitic alteration of wall rocks, which is due to the action of fluorine, doubtless escaping from the ore magma at this critical juncture, becomes clearer. At Tonopah, for example,[39] there has developed, in the wall rocks near the quartz veins, sericite and adularia, together with quartz, pyrite, and siderite; at a distance from the veins the type of alteration changes, and calcite, chlorite, pyrite, and siderite are the important minerals. There are transitions between these two types, and my conclusion was that they were formed by the same solutions, working out from the vein fissures. The sericite (muscovite) and quartz of the vein walls indicates fluorine disengaging itself on the precipitation of quartz, together with carbon dioxide and hydrogen sulphide (as indicated by the pyrite and siderite[40]; but at a distance from the vein only carbon dioxide and hydrogen sulphide were left. This succession corresponds with the recorded succession of gases from volcanic fumaroles. The hottest fumaroles (over 500° C.) contain chlorine, fluorine, and boron, which disappear when the temperature sinks. Sulphurous emanations persist to a much lower temperature, and carbon dioxide is given off freely till the temperature is relatively low, although it occurs also in the hottest ones.

The upper pressure-limit for the retention of the integrity of ore magmas, or the limit where the gases and water are disengaged, forcing the precipitation of silica and other

[39] J. E. Spurr: *Professional Paper* 42, U. S. Geol. Surv., 1905, p. 207.
[40] *Econ. Geol.,* Vol. X, 1915, pp. 713-769.

solid constituents, appears to be within a few hundred feet of the surface, as I have repeatedly stated; it may be provisionally fixed at not more than a thousand feet.

There are instances in mining districts where the top of a vein is shown, above which comes a barren fissure, or barren quartz.

In the Carmen mine (Fig. 87), at Guanajuato, Mexico, which I have visited, the main outcrop is simply a slightly discolored yellow zone of rhyolite, with no quartz or other vein material, along a single fault slip, evidently of no

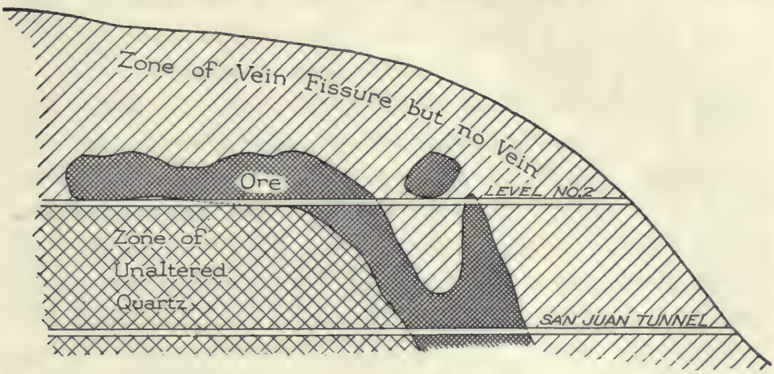


FIG. 87.—Guanajuato, Mexico; Carmen mine. Vertical longitudinal sketch section along Carmen vein. There is no vein at the surface—only a tight "fissure"; at a certain depth come rich silver sulphides (the ore); and below this is a quartz vein. The upper pressure-limit of ore magmas is here thought to be illustrated. By J. E. Spurr.

great magnitude. It would never be taken for a vein. This extends down about 450 feet and contains no values. Below this for about a hundred feet or more the decomposed rock along the fault slip is black, containing silver, principally argentite, and is the best ore of the mine. Below this comes the top of a weak quartz vein (with some calcite) containing argentite, and rich in spots; and this was followed down, at the time of my visit, to about 800 feet from surface. The zone of black decomposed rocks which forms the main ore follows closely the present surface. I was tempted, of course, at first to consider this a zone of "secondary enrich-

ment" by descending waters, and as sketched it would seem to be very plausibly that: but the embarrassing circumstance is that there is no vein whatever above it; therefore, I was soon convinced that the ore was primary, and that we had here the real "top" of a vein. Its conformity to the surface shows that the surface at the time of its deposition was of the same configuration as at present: of course, it has been lowered by erosion since then, but the lowering cannot have been more than a few hundred feet, otherwise the surface contours would have tended to become much altered; so that the upper pressure-limit which determined the top of the vein could hardly have been over a thousand feet from the surface. The rich zone of argentite, impregnating the rhyolite for a hundred feet above the top of the quartz vein zone, appears to be an interesting example of the process, which I have frequently mentioned, of the partial dissociation of the metallic minerals from the silica, on the crystallization of the latter. We are familiar with this phenomenon as shown by sulphides filling cracks in the quartz, or impregnating the wall rocks, or occurring in the roof of a flat quartz vein (p. 524), but here in the Carmen the sulphides cap the quartz. In the Guanajuato district there are other instances of rich veins showing no cropping, or a barren one; and where nevertheless the ores are primary. They consist mainly of the various silver sulphides, with copper and iron pyrite, galena, and blende; the gangues being quartz, adularia, calcite, and some siderite, fluorite, and apophyllite.

From what I have read concerning the Tonopah Divide mine, near Tonopah, I suspect that this may possibly be a similar case. The silver-bearing lodes in the Divide district, according to Dr. Knopf,[41] are in rhyolitic rocks. They do not outcrop, and were discovered accidentally in prospecting gold veins of somewhat different type. The ore comes within 50 to 150 feet from the surface, or is deeper, and

[41] Adolph Knopf: "The Divide Silver District, Nevada." Bulletin 715-K, U. S. Geol. Surv., 1921, pp. 147-169.

consists mainly of cerargyrite (hornsilver), with some argentite, from which the hornsilver is thought by Knopf to be derived: "The outcrops of the lodes are rather lightly iron-stained by disseminated limonite, and this staining is the only evidence likely to suggest that the fracture zones are mineralized." The ore is associated with a conspicuous development of sericite, in seams; and these seams are often very rich, and contain coarser cerargyrite. Calcium molybdate (powellite), in part altered to molybdite (hydrous ferric molybdate), occurs locally. The rich ore, which occurs beneath the barren superficial portion, is of limited vertical extent, and beneath it the lode has a few thin veinlets of quartz, and is sparsely impregnated with pyrite. Knopf explains the rich ores as due to leaching and concentration by descending waters; and interprets the upper barren or "no-vein" zone as having been thoroughly leached. He assumes that the original concentration of silver from the upper zone by descending waters was to argentite, and that this secondary sulphide zone was subsequently altered to chloride by surface waters. But at Tonopah, only four miles away, it was the *outcrops* that were rich in silver chlorides, and indeed that is characteristic of the whole region.

At Tonopah there has been no marked zone of enrichment, with evident relation to the surface, of any kind, formed at any time: the ores, oxidized and sulphide, were rich from the outcrop to the lowest depths at which they have been found. If anything, the ores of the most superficial zone were the richest. Moreover, the lack in the Divide outcrop (according to the descriptions) of even those few quartz stringers and that partial silicification of the lode which characterizes the lode in depth suggests to me that the vein may never have reached the surface, and that the zone of argentite was primary and represented the crown of the ore deposition, dropped at the critical upper pressure-limit, parallel to the surface, at some recent geological date when the surface was roughly parallel

with the present, but some hundreds of feet, probably, higher. The close association of sericite and rich ore also indicates that the position of the ore is the original primary one, since sericite is a mineral derived from the action of ascending fluorine-bearing waters.

The important Waihi gold mine, in New Zealand, shows, according to the accompanying cross-section (Fig. 88), lodes which terminate above—along a plane parallel to the surface. These are Tertiary shallow-formed veins. The termination of the lodes may be due to the ore magma having reached the critical zone of pressure-relief, as inferred for

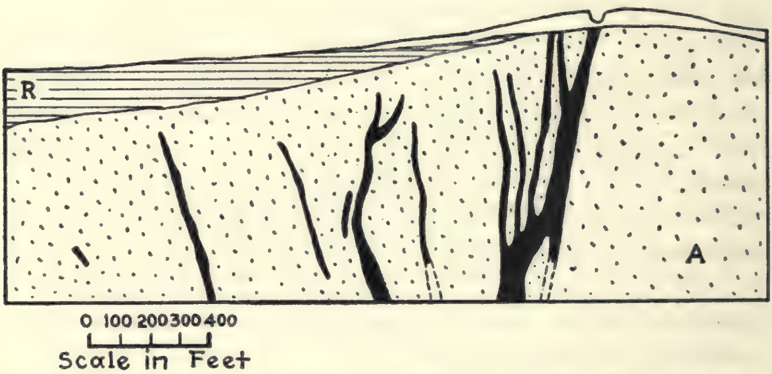


Fig. 88.—Shows apparent termination of fissure veins near and parallel to the surface, perhaps by reaching critical zone of pressure-relief. Cross-section of Waihi Gold Mine, New Zealand. A, Andesite and dacite; R, post-mineral rhyolite. After C. Frazer; Bulletin 15, New Zealand Geological Survey (slightly adapted).

the Carmen mine at Guanajuato. As I have no personal knowledge of this Waihi district, my conjectures are based only on the illustration, and are, therefore, naturally, tentative only.

Besides Cripple Creek, Colorado affords another instructive example of a slightly dissected volcanic neck which contains an ore deposit: about forty miles south of the Cripple Creek district, at Silver Cliff, in the Rosita Hills, is the old Bassick mine, which I have never seen, but which

has been described by Emmons[42] and Cross.[43] Here Tertiary volcanic rocks, as at Cripple Creek, have broken through pre-Cambrian granite and gneiss. As at Cripple Creek, different lavas were erupted one after the other, indicating differentiation of an underlying magma which was in a way similar (and here is an interesting fact) to the Cripple Creek magma, both being unusually alkaline. The order was (1) andesite, (2) dacite (quartz-andesite), (3) rhyolite, (4) andesite, and (5) trachyte. The next volcanic event was not an intrusion, but an explosion of gases, clearing a volcanic chimney and hurling fragments of rock into the air, many of which fell back and filled the crater. This infilling or agglomerate is made up of angular and rounded fragments up to several feet in diameter, with the chinks filled with finer material. The fragments consist of andesite, also of the granite and gneiss on which the volcano rested. Charcoal is occasionally found to a depth of several hundred feet, and is supposed to be the remains of trees growing on the volcano at the time of eruption, which after being hurled upward by the explosion fell back into the open pit. This charcoal is a valuable bit of evidence, as showing that the part of the crater chimney now occupied by it cannot have been many hundred feet below the surface at the time of the explosion. After the explosion, the chimney-filling was pierced by an ore deposit, which accordingly could not have been formed at a depth, below the then surface, over say a thousand feet greater than its depth below the present surface. Still later came a basic dike (porphyritic olivine basalt, or "limburgite"). Note that the lava succession in both Cripple Creek and Silver Cliff was closed by dikes of basalt porphyry ("limburgite" and "monchiquite"); but that the ore deposition at Cripple Creek succeeded this basalt, and at Silver Cliff immediately preceded it. This will give us again a vivid conception of the sharply clear-cut nature of ore deposition at both

[42] *Seventeenth Ann. Rep.* U. S. Geol. Surv., Part 2, 1896, pp. 269-472.
[43] Spanish Peaks Folio, 71, U. S. Geol. Surv., 1901.

places: that it was one of the distinct events of the volcanic invasions, the result of one of the differentiated emissions sent up from time to time, from the busy magma beneath, by the gateway which had been established through the granite crust, whose surface exit was the volcanic cone. The numerous, repeated and quantitatively more important lavas of the volcano were all earlier, and they were not attended nor followed by ore deposition: therefore, ore deposition (in both these cases) did not result from the emanations from cooling lavas. Moreover, it neither resulted from leaching of the rock by percolating waters (whether ascending, descending, or laterally moving), nor was it formed by hot-spring action derived from the waters given off by cooling igneous rocks: its sharply punctuated time limitations rule out these methods. It did follow up the channel which had been cleared by the preceding eruption, and so was derived from the same general source as the pent-up gases which blew out the volcano.

At both Cripple Creek and Silver Cliff, the volcanic succession started with an intrusion of intermediate composition. At Silver Cliff it was andesite, which was repeated in several gushes; the andesite was followed by quartz-andesite and this by rhyolite, clearly a differentiation series increasing in silica content; then there was another succession of andesite lavas, which similarly indicates an increasing content of silica and alkalies. And next came the ore magma and finally the basalt. Evidently, the main magma was an intermediate one; and two cycles of differentiation are suggested. Fossil leaves in the rhyolite which terminated the first differentiation series indicate an early Eocene (very early Tertiary) age.

The Cripple Creek volcano has been considered Miocene or Pliocene (late Tertiary). At Cripple Creek there is exhibited only a single cycle of differentiation: the first eruption, syenite (or latite-phonolite), was intermediate; the next, phonolite, representing a more alkaline magma; followed by basaltic dike rocks, a more basic type. This

cycle of differentiation seems to correspond with the second cycle at the Rosita Hills, for both represent the differentiation of a special type of alkali-rich magma, which is also present, as shown by Ball, at Idaho Springs in Colorado, some 75 miles north of Cripple Creek.[44] From the similarity of the alkaline lavas at Cripple Creek and at Rosita Hills, it has been assumed that they were contemporaneous.

These evidences at Cripple Creek and at Silver Cliff are reliable proof of my earlier conclusion that the ore deposits in volcanic rocks near the surface are also (like the deposits associated with porphyritic dike rocks in the intermediate depths and those associated with granular rocks at the greater depths) differentiation products, and not the result of emanations from cooling volcanic rocks; that they ascend direct from the magmatic laboratory in depth, like the igneous rocks with which they are associated; and that they occur so near the surface on account of the relatively high temperature of the crust, which causes the ore magma to remain fluid till quite near the surface, when the crystallization takes place within a relatively short vertical space, and without the refinements of successive precipitations (constituting the orderly successive zones characterized by the different metallic sulphides) which are found under favorable conditions (of slow cooling in rocks which grow cooler very, very slowly upward) at greater depths.

I conclude, therefore, that ore deposits may be formed up to within about 500 feet of the surface, in heated volcanic rocks, by a typical ore magma derived from magmatic differentiation, and ascended from the depths; but that these ore deposits do not reach the surface, for the reason that the ore magma (if, by virtue of sustained heat in the rocks, it reaches within a few hundred feet of the surface without partial or complete crystallization) experiences finally a disintegration, the relieved pressure permitting the dissociation of the contained gases which were part of the

[44] SPURR, GARREY and BALL: *Professional Paper* 63, U. S. Geol. Surv., pp. 83, 134.

magma, which gases, with water vapor and traces of the metals, ascend to the surface, while the most of the solid non-volatile or less-volatile components of the magma, mainly silica and metallic sulphides, are perforce precipitated by the abstraction of the gases, forming, naturally, often unusually rich ore deposits of limited vertical extent. A similar precipitation takes place at greater depths—indeed, at any depth—on account of diminished temperature only, but gradually and according to temperature zones. Therefore the ore magmas owe their integrity to both heat and pressure: they ordinarily are crystallized by reduced heat; but if the heat remain elevated, then, at any rate, quite close to the surface the diminished pressure brings about their crystallization and prevents their reaching the surface. Furthermore, I conclude that wherever the congealing takes place, at any depth, the tendency is for the silica to solidify first, and the metallic sulphides later if opportunity offers, so that these sulphides may appear as partly later deposits, often in the same vein, often again removed more or less from the quartz by migration outward and especially upward before deposition. Where the consolidation of the ore magma takes place suddenly, close to the surface, it may happen that the metals tend to overlie the gangue (mainly silica) deposition.

Where the consolidation of the ore magma takes place in depth, the aqueous vapor residual from the consolidation—of both silica and metals—cooling somewhat, may ascend to the surface as hot springs, alkaline and carrying gases, and these may contain, carry away, and deposit the most volatile of the metals of the magma, notably mercury, and to a less degree arsenic and antimony, which are deposited as simple sulphides, whereas in the ore deposits proper they enter into more complex sulphides. Where the ore deposition takes place very close to the surface, the temperature being elevated, these more volatile metals, together with the aqueous and other gases, appear in fumaroles, which are thereby to be sharply distinguished

from the invariable fumaroles which mark all cooling lavas, just as the corresponding hot springs which deposit cinnabar and other sulphides are to be distinguished from hot springs in general, which, even though they may be magmatic, have nothing to do with magmatic ore deposition, since they are not residual from the ore magma, but, like the invariable surface fumaroles, represent the water exuded from all igneous rocks on crystallization.

CHAPTER XII

The Derivation of Certain Ores from Certain Kinds of Magma

This chapter calls attention to the fact that certain ore deposits are closely allied to basic rocks; others to siliceous rocks. Chromite, ilmenite, nickel, and platinum are restricted to the former; tin, tungsten, and molybdenum to the latter.

Study of the platinum-chromite deposits of the Urals, as reported by Duparc and Tikonowitch, indicates the origin of the dunites, in which the platinum and chromite occurs, by magmatic differentiation. The cause of magmatic differentiation is suggested to be differential vapor-tension between the various elements in magmas, effecting segregation under certain temperature-pressure conditions. Thus, also, are explained the accumulation of metallic oxides and sulphides, in the magma, on the margins, or in the wall rocks at varying distances from the igneous contact.

Certain metals, like copper, arsenic, lead, and zinc, are common to both types of magma; but in these cases there are characteristics of gangue and the alteration of wall rocks which enable the diagnosis of their origin. Such metals are also derived from intermediate magmas, and their ores show correspondingly intermediate characteristics.

THERE ARE SOME METALLIC ORES which cling closely to certain kinds of igneous rocks. For example, chrome ore is associated with very basic rocks; tin ore with siliceous rocks. The former is never found closely associated with siliceous nor with intermediate rocks; nor the latter with basic rocks nor with intermediate rocks. They form the best examples and the most perfect types of this kind of association.

Tin ore, as has long been known and pointed out, has been derived from granite magma from which still more extremely siliceous ore magma originates through differentiation. Pegmatites occur, tin bearing, and these grade off into tin-bearing quartz veins. The ore is almost invariably

the oxide—cassiterite; and it is associated typically with gangues like topaz, fluorite, muscovite, and tourmaline, which contain fluorine and boron, and testify to the abundance of gases in the tin ore-magma, and in the pegmatite magma, so that this particular tin-bearing form of an ultra-siliceous magma corresponds with what I have termed a superpegmatitic magma (Chapter VII). For tin ores we must apparently have first of all an underlying tin-bearing metallographic province, as I sketched out in Chapter X; next it is necessary that we have granites and alaskites, for the tin of the original magma will apparently have been entirely drawn off into these siliceous differentiates; and finally the carriage of the tin seems to have depended largely upon the more powerful magmatic gases.

On the other hand, take chromium. That has been drawn off into (or remained with) the basic differentiate in certain provinces where it occurs.[1] Like tin, it occurs as an oxide (of chromium and iron—chromite); so both are high-temperature minerals and close to the rock magma. Chromite is at home in the peridotites, which are olivene-pyroxene rocks, and in olivene diabases, which are olivene- (soda-lime) feldspar rocks. Olivene (which is a silicate of magnesia and iron) is, therefore, its closest associate. In these rocks, disseminated chromite, on account of its free crystalline outline, has often been held to be older than the silicates, and to be the first mineral to form. There is some doubt about that—at any rate, it appears certain that it is sometimes a late mineral, for rarely it forms regular veindikes, as in instances in Montana and Ontario.

In that respect, it is somewhat like magnetite, which also has been held, and for similar reasons, to have been a mineral earlier to crystallize in the magma than the silicates. But certain investigations show that these intrusive iron

[1] The origin of chromite and certain other ores, like those of nickel and titaniferous iron, by magmatic segregation from very basic magmas, was first pointed out by J. H. L. Vogt in 1893, and his conclusions have been universally accepted, and many subsequent corroborating studies have been made by others, especially, in America, by Joseph Hyde Pratt.

ores were probably not crystallized from a dry melt, not even to the degree that the associated igneous rock is, but that the fluid form was a subsequent and residual magma. The non-titaniferous magnetite ores at Cranberry, North Carolina, for example, have been described by Prof. W. S. Bayley[2] as intrusive: "The intrusion was apparently a magnetitic pyroxene-pegmatite, followed later by an intrusion of pyroxene-magnetite, and finally by one of magnetite." Clearly a process of differentiation. By a similar process, magnetite ores may locally be formed from the pegmatitic magma of siliceous rocks, as near Idaho Springs and Georgetown, Colorado, as described by Ball and myself.[3] A most instructive and convincing argument as to the period of crystallization of the magnetite in many igneous rocks is here afforded. The granite, in which the magnetite-bearing pegmatite occurs, itself contains scattered crystals of magnetite, having the form and isolated habit which has always been considered as a proof that they formed earlier than the other minerals (like feldspar and quartz) which inclose them; but it was noted in some instances that near the walls of a magnetite-bearing pegmatite, even of a very little vein or gash of this pegmatite, the isolated magnetite crystals in the granite become more abundant, and so lead up to solid magnetite veinlets, or to a magnetite-bearing pegmatite veindike. These isolated magnetite crystals in the granite, therefore, were the latest of the rock minerals to be deposited, and belonged to the residue of the magma.

The complex history of crystallization of igneous rocks, especially of plutonic rocks, has not been studied with sufficient attention. It has been assumed that there was a succession of crystallization from a fluid magma, the test of age of minerals being freedom of crystallization, or "idiomorphism"; and that this was about all there was to

[2] *Econ. Geol.,* Vol. XVI, March, 1921, p. 150.

[3] SPURR, GARREY and BALL: *Professional Paper* 63, U. S. Geol. Surv., pp. 61, 182. These are of scientific interest only.

it. I have demonstrated in the observations above cited and elsewhere (p. 572) that the idiomorphic test is not conclusive: that certain solutions have the property of passing through solid rock, without visible channels and leaving no trace, and forming new minerals by replacement of the necessary space in already-formed older minerals. This is certainly the case with much of the magnetite in the granite in Georgetown, as instanced by the above. I see no reason why it is not the case with all the magnetite of these rocks. Moreover, I am inclined to the hypothesis that the so-called "accessory" minerals of granites (all, like magnetite, generally considered as the first minerals to crystallize, for the crystallographic reasons above noted) may be in this respect in the same class as the magnetite. Let us see what they are: besides magnetite, they include zircon, tourmaline, fluorite, apatite, pyrite, titaniferous magnetite or ilmenite, and others. Zircon is found in the Idaho Springs pegmatites, practically contemporaneous with the magnetite; and although the direct proof that this is of the same age as the scattered small crystals of zircon which form one of the constituent accessory minerals in the granite was not observed, as it was very satisfactorily in the case of the magnetite, yet it is a permissible hypothesis that it is so. Similarly, Ball noted[4] apatite in the pegmatite which cuts the granite; and also found that apatite, like zircon, is an abundant microscopic constituent of the granite. No tourmaline was noted in the pegmatites: and tourmaline is not noted as a microscopic constituent of the granites! In general, many of these granitic "accessory" minerals contain powerful magmatic gases, such as boron (tourmaline), fluorine and chlorine (apatite), or sulphur (pyrite), testifying to these gaseous agencies controlling their deposition.

That these gaseous elements of the magma are not early "fixed" in mineral form is well known: they are, on the contrary, concentrated and active in the residual pegmatitic

[4] *Op. cit.*, p. 63.

magmas and the still more highly evolved ore magmas. Certain proportions of these elements are doubtless "trapped" by the consolidation of the magma: and my conception is that these may build the crystals of this "accessory" group of minerals in the body of the igneous rock, probably (in spite of the idiomorphic outlines) largely as a final crystallization: but that a certain proportion collects along fissures or in weaker parts of the rock or becomes part of a residual pegmatitic magma which forms veindikes containing these same "accessory" minerals, which are practically of the same origin and contemporary with those in the body of the rock; and also forms, in the rocks near these fissures, the same "accessory" minerals as an integral part of the igneous rock texture. These gaseous elements are operative, of course, in surface volcanics as well as deep granular rocks, but by no means so actively; accessories like zircon, apatite, and magnetite, for example, occur in rhyolites, but not so characteristically as in granites. Muscovite, formed by the action of fluorine, which determines the crystallization of that mineral instead of orthoclase, is very rare in rhyolite, but is characteristic of granites, and even, in some deep granular rocks, may replace the alkali feldspar entirely, creating, instead of a quartz-orthoclase rock (alaskite) a quartz-muscovite rock (beresite).[5] The slow crystallization and the pressure at depth which help to prolong the retention of these gases promote the crystallization of those minerals which depend on these elements for their formation.

The oxides, like cassiterite, chromite, magnetite, specular iron, zircon, rutile, ilmenite, corundum, all have evidently formed at an elevated temperature, as I have elsewhere noted, and so are nearer the rock magma, and form with a greater though varying degree of closeness a part of it, than the sulphides. Pyrite, although it occurs in isolated crystals in igneous rocks, and has, therefore, been regarded in the past by some petrographers as one of the earliest

[5] J. E. Spurr: *Am. Jour. Sci.*, Fourth Sec., Vol. X, 1900, p. 351.

minerals of the rock, is probably usually later than magnetite or specular iron, and formed at a lower temperature; and the same observation will, I believe, hold true of other sulphides.

Chromite has this peculiarity, that, unlike many of the other "accessory minerals" of igneous rocks, for which I have inferred in large measure at least a deposition subsequent to the silicates, it does not occur in pegmatites. Therefore, its lower temperature-limit of crystallization is higher than that of the pegmatites, so that it may be regarded as more truly and exclusively a rock mineral. In this respect it is somewhat like ilmenite, for ilmenite is rarely a pegmatitic mineral, although as a rock mineral it is proved in many cases to have crystallized after the silicates: ilmenite has often segregated or differentiated into a partially or completely independent magma, and forms streaks or even dikes in the earlier, predominantly silicate rock (norite or anorthosite). The high temperature at which chromite has crystallized is shown by the occurrence of the mineral in meteoric irons; and also by the occurrence of small diamonds in chromite.[6] Nor is chromite (in which it now distinguishes itself sharply from tin) associated with the familiar gas-formed gangue minerals, like tourmaline, apatite, or muscovite. Apparently, its exclusive association with basic rocks consists in part in this, that it is not a companion of the gaseous elements, just as the exclusive association of tin with granitic rocks must be due to its being a close accompaniment of these elements, which at high temperatures and pressures have also been very likely responsible for the solution of the silica and its retention in the fluid state, and gradual extraction to form siliceous rocks (growing more siliceous, like granites and alaskites) and finally the siliceous ore magmas.

Ilmenite is not associated mainly with olivene rocks (peridotites), but with lime-soda feldspar rocks, containing also orthorhombic pyroxene (hypersthene or enstatite)—

[6] R A. A Johnson: *Mem.* 22, Geol. Surv. of Canada, 1913, p. 1E.

such rocks as pyroxenites, norites, and gabbros. Hypersthene is an iron-magnesia silicate, enstatite a magnesia silicate. As compared with the peridotites, the norites are less basic, since the former contain no feldspar, and olivene contains more magnesium and iron (over 50 per cent and up to 60 per cent) than enstatite and hypersthene (which run around 40 per cent or less). Here is a definite preference among basic rocks, chromium being apparently only soluble in a highly concentrated magnesia lime-iron silicate solution containing little aluminum, while titanium is not soluble in this strong basic solution, but is soluble in a somewhat more siliceous solution, containing a great deal of aluminum, but very much less magnesium, and about the same iron and lime. Chromium and magnesium seem to be, therefore, elements which are for some reason chemically coupled in the peridotites, as titanium and aluminum are in the norites. Titanium, unlike chromium, is not entirely insoluble in a silica-gaseous magma, and so does appear in pegmatites, both as the iron-titanium oxide, ilmenite, and as the titanium oxide, rutile.

Chromite and tin are types of the metals which are exclusively associated with basic and with siliceous rocks respectively. Characteristic of the basic rocks only, again, is nickel; and of the siliceous rocks only, tungsten and molybdenum. The association of nickel is much like that of chromium, in that it is found associated often with peridotites; but also like that of ilmenite, in that it occurs associated with diabases, norites, and gabbros, so that its range of association with igneous magmas, though closely restricted to the basic magmas, has more latitude than in the case of chromium or even the bulk of the titanium. The great nickel deposit at Sudbury, Ontario, occurs in connection with an extensive intrusion of basic-intermediate rock which has undergone differentiation, and grades from a norite in its lower part to syenite in its upper part. No chromium is associated.

Nickel does not occur as a primary oxide, but as a sul-

phide, and, therefore, in accordance with what appears to be the rule, has been deposited at a lower temperature, and is a later crystallization than the oxides. Tolman and Rogers[7] give the order of crystallization in magmatic sulphide ore deposits as: silicates, magnetite, hematite, pyrrhotite, pentlandite, chalcopyrite, and bornite. In brief, this means: silicates, oxides, sulphides. This is probably true not only for ore deposits, but for the crystallization of igneous rocks as well; and, indeed, the distinction between these two will be sometimes difficult to define. Metallic ores of this type, closely associated with and allied to certain igneous rocks, have not necessarily formed from a dry melt, although relatively dry ore magmas of the "aplitic" type (Chapter VII) are common, especially in the basic-magma-derived group; indeed, the parent or associated igneous rock magma also has had its share, much like the ore magma, of water and other elements, which (together with selected mixtures, making favorable—eutectic—solutions) tend to keep magmas fluid at temperatures far below that at which we can fuse the rocks as finally solidified, and have determined sequences of mineral crystallization different from those suggested by their relative fusibility from the crystalline condition.

At Sudbury the nickel-bearing ore magma was plainly a product of differentiation, and this differentiation sorted out copper as well as nickel. The succession, in brief, as shown by successive intrusions, was: 1, Diorite, which separated into a norite in its lower part and a granite-syenite in its upper; 2, granite dikes; 3, ore veindikes; 4, diabase dikes; 5, olivene-diabase dikes. In the ore veindikes there is usually no gangue, but occasionally there is a little contemporary quartz and calcite; this fixes the temperature of crystallization of these veindikes as below the temperature (which is about 500° C—see Chapter VII, p. 319) below which quartz and calcite are formed, and

[7] "A Study of the Magmatic Sulfid Ores." Stanford Univ. Pub., Univ. Ser., 1916.

above which lime silicates are formed. According to this criterion, the temperature of the chalcopyrite deposition was not higher than in chalcopyrite deposits connected with siliceous rocks, as a result of deposition from the ultra siliceous end-product magma, as described, for example at Matehuala, in Mexico; indeed, the indications are that it was deposited at about the same temperature.[8]

Of the list of minerals at Sudbury, we have at Matehuala, in Mexico (p. 258), abundant pyrrhotite, chalcopyrite, and sphalerite; but we do not have the nickel and platinum minerals, nor do we have nickel (or platinum) associated with any of the copper ores derived from the final differentiation of siliceous rocks; though we do often find them in copper ores derived from the final differentiation of basic rocks. At Matehuala, we have arsenic in the form of arsenopyrite, which has not been reported from Sudbury. The Encampment district in Wyoming, which I have studied in association with Dr. Spencer, contains copper ores derived from the differentiation of basic rocks, and the Rambler mine, in this district, besides copper (chalcopyrite), contains platinum (sperrylite) as at Sudbury; but nickel is here lacking.

Platinum is another element which, like chromium and nickel, is practically confined to basic rocks.

Duparc and Tikonowitch,[9] in their monograph of the platinum of the Urals, describe the occurrence not only of platinum, but incidentally of chromite, magnetite, and ilmenite, in the basic intrusive rocks of the Ural province. The principal "mother rock" of platinum is dunite, consisting of 97 to 99 per cent olivene and 1 to 3 per cent chromite. A much less important matrix of platinum is

[8] Since the above was written, Wandke and Hoffman have announced (p. 597), as metasomatic minerals formed in the granitic walls of sulphide veins at the Creighton mine at Sudbury, the presence of hornblende, biotite, and albite. The formation of hornblende, especially, corroborates the above conclusions (pp. 263, 264).

[9] "Le Platine et les Gîtes Platinifères de l'Oural et du Monde," Genève, 1920.

pyroxenite, containing olivene and pyroxene. The gabbros in general are barren. Around the basic intrusive rocks are the schists into which the igneous rocks have

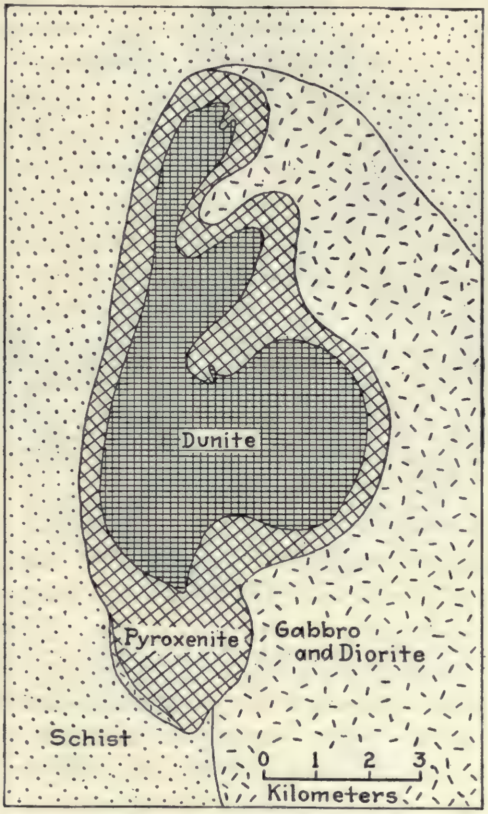


FIG. 89.—Geological map of the platinum-bearing district of Taguil, in the Ural Mountains. From Duparc and Tikonowitch: "Le Platine et les Gîtes Platinifères"; Geneva, 1920. Fig. 1.

The map shows the successive concentric shells of igneous rock—dunite, pyroxenite, diorite—produced by magmatic differentiation after the intrusion of the magma into the schists.

been intruded as a whole, for all are in general contemporaneous. These three major types of rock have a remarkable relation of position. (Fig. 89).[10] Where the dunite occurs, it is typically in a rudely elliptical outcrop, and is

[10] *Op. cit.*, p. 45. Fig. 1

surrounded by a ring of pyroxenite, and also carries residual fragments of a pyroxenite "cap." Dunite dikes cut the pyroxenite. Around the pyroxenite is a rude peripheral ring of gabbro, which also occurs rarely as fragments of a residual cap[11] on the pyroxenite. The relation of these successive rings is assigned by the authors, and with unquestionable correctness, to magmatic differentiation; and they even postulate that it is indicated that at greater depth a still more basic rock, heavy in iron, like that of the meteorites, will occur. Chromite is, of course, (by definition) characteristic of the dunite; similarly, magnetite (frequently titaniferous) is characteristic of the pyroxenite,[12] a fact which illustrates my previous coupling of olivene and chromite, or magnesium and chromium; and pyroxene and ilmenite, or aluminum and titanium.

In the dunite, the chromite occurs in little cubes or octahedra, disseminated through the olivene,[13] or is segregated into nests or compact bodies.

The magnetite (frequently titaniferous) of the pyroxenites is especially abundant in an olivene-rich phase; this iron (titanium) oxide is, in this phase, a later crystallization than the olivene and pyroxene.[14] (Fig. 90). In the so-called plain pyroxenites (which nevertheless contain olivene) the magnetite occurs only in little crystals included in the other minerals; but in types transitional between the olivene-rich and the olivene-poor pyroxenites, the two habits of magnetite are shown together.[15] Magnetite forms solid segregations in the pyroxenite, as the chromite does in the dunite. In the gabbros, the magnetite occurs cementing grains of olivene, hence is later,[16] and also occurs in little crystals in the pyroxene.[17] This latter habit is more characteristic of the less basic gabbros, the former habit of the more basic.[18] As a matter of fact, some drawings of thin

[11] *Op. cit.*, p. 48.
[12] *Op. cit.*, p. 51.
[13] *Op. cit.*, p. 53.
[14] *Op. cit.*, p. 76. Fig. 5.
[15] *Op. cit.*, p. 79.
[16] *Op. cit.*, p. 89.
[17] *Op. cit.*, p. 91.
[18] *Op. cit.*, p. 97.

sections[19] show both habits in a single microscopic slide.

Dike rocks representing all stages and combinations of differentiation are numerous. A basic porphyry contains

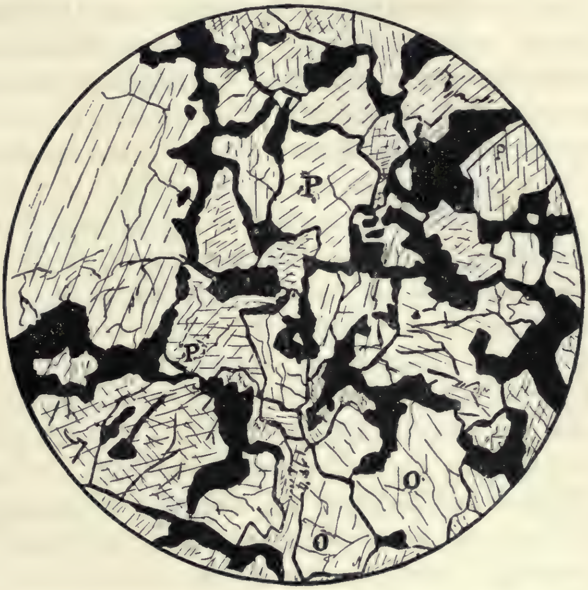


FIG. 90.—Section of pyroxene-olivene-magnetite rock, showing magnetite (solid black) the last mineral to form. P, Pyroxene; O, olivene. Ural Mountains, Russia. After Duparc and Tikonowitch; Fig. 5, p. 76. The later age of the magnetite is also shown in the olivene rock (dunite); see Duparc and Tikonowitch, p. 120, Fig. 19.

both chromite and magnetite,[20] the former in isolated octahedra and the latter in little irregular splashes. Others[21] contain magnetite both in isolated idiomorphic grains and in irregular spots, while still others show only one of these habits (according to the writers).

The platinum of the dunites is closely associated with the

[19] *Op. cit.*, Fig. 9, p. 93; Fig. 14, p. 105.

[20] *Op. cit.*, p. 123.

[21] *Op. cit.*, pp. 129, 133.

chromite, but always a later crystallization.[22] In the pyroxenites the platinum was the last mineral to crystallize; it is found closely associated with the magnetite, but is younger.[23] Hence the authors consider, as I think correctly, that in the olivene-rich pyroxenites the order of crystallization was: 1, olivene; 2, pyroxene; 3, magnetite; 4, platinum; but in the olivene-poor pyroxenites they place the succession as 1, magnetite; 2, olivene; 3, pyroxene; 4, platinum; in which I think they may be mistaken as to the position of the magnetite, which, from their own descriptions, I should assign the same position as they give it in the olivene-rich varieties. The assignment of the early age of the magnetite (in some cases) rests on its occurring as isolated crystals included in the other minerals; but I have shown at Georgetown[24] and elsewhere that this criterion is not reliable, and the notes I have given above of the descriptions (by Duparc and Tikonowitch) of the habit of magnetite in the various pyroxenite and gabbro phases, fluctuating between the isolated or disseminated habit and that where the magnetite cements the silicates and so is clearly later (the two habits indeed occurring at times at least in a single specimen), leave little doubt in my mind that all the magnetite is of one generation, and that the isolated or disseminated crystals have formed by replacement.

This principle of dissemination of small idiomorphic crystals so that they are inclosed in older minerals being established, we should inquire how far it is operative, and if of all minerals. Quartz forms in limestone according to this law, as I have shown at Aspen[25] (Fig. 91), but it has not been described as having this habit in igneous magmas, although it is here usually a late mineral. Neither does feldspar, so far as has been determined, affect this habit in

[22] *Op. cit.*, p. 197.

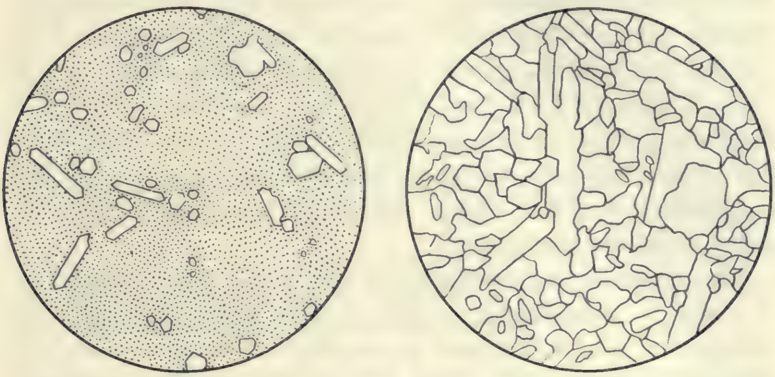
[23] *Op. cit.*, p. 204.

[24] See p. 562.

[25] *Monograph* XXXI, U. S. Geol. Surv., p. 219.

magmas. In general, in the magmas, this penetrative power seems to be denied the ordinary rock minerals like quartz, feldspar, and ferromagnesian silicates; and restricted to the oxides and the later sulphides, and such other minerals, like apatite and tourmaline, as crystallize by virtue of gaseous elements.

The characteristic and highly significant relation of the dunite "centers" in the Urals to encircling rings of pyroxenite, and still outer rings of gabbro (which becomes still



a b

FIG. 91.—**a** and **b**, development of isolated quartz crystals in limestone. Aspen, Colorado. **a**, Early stage; **b**, stage of complete silicification. Limestone is entirely replaced by silica, and becomes "jasperoid." Described by J. E. Spurr: Monograph XXXI, U. S. Geol. Surv., p. 218.

more significant when it is encountered in other parts of the world, as in British Columbia and other parts of Canada), is an arrangement as seen on the plane of the earth's surface. The circumstance recorded by the writers of the monograph (Duparc and Tikonowitch) that fragments of a cap, of either of the outer rings, are frequently found on the next inner rock, shows that in cross-section the whole intrusion was in the form of a dome, with concentric layers, dipping presumably rather flatly away from the summit. A cross-section, therefore, would show the dunite at the bottom, the pyroxenite above, and the gabbro at the top. Since there are gradations between all these, evidently

here is a single basic intrusion, which thrust its dome-like head up into the schists as a homogeneous magma, and was differentiated after intrusion, as the general parallelism of the zones of differentiated rocks to the dome periphery shows. Here is a demonstration of what I have previously inferred (see p. 231): that differentiation takes place in magmas only when they attain a certain elevated zone in the crust, and come under critical favorable conditions, which I have earlier always assumed to be very slowly developing crystallization. In other words, I recognized a critical zone of differentiation, more or less parallel with the earth's surface, which I defined as being in the lower part of the zone of crystallization.[26] I believe that this Russian occurrence and like "dunite" centers and surrounding rings elsewhere afford a very convincing proof of this conclusion, and will throw further light on the nature of differentiation processes.

The downward succession in the Urals from gabbro at the top to pyroxenite in the middle and dunite at the bottom, or (for sometimes no dunite center is exposed by erosion) from gabbro above to pyroxenite below, suggests immediately that gravity has been the cause of the differentiation, and that the process has been the one of "gravitative settling" so often appealed to. Examined a little closer, this theory is not tenable, because the zones of rock are not parallel with the earth's surface, as they would be if due to settling, but are parallel with the surface of the intrusive dome. The characteristic surface arrangement of successive rings would not appear if due to gravitative settling. Moreover, gravity does not explain the practical restriction of chromite (gravity 4.32-4.47) to the lowest zone (dunite) and the practical restriction of (titaniferous) magnetite (magnetite, gravity 5.168-5.180; ilmenite 4.5-5.) to the middle (pyroxenite) zone. The heavier oxide overlies the lighter. Nor even does it explain the almost

[26] *Econ. Geol.*, Vol. II, No. 8, Dec., 1907. "A Theory of Ore Deposition," pp. 782-784, 790.

exclusive olivene (gravity 3.27-3.37) of the bottom layer, as compared with the almost exclusive pyroxene (diopside-diallage series, gravity 3.2-3.38) of the middle layer. There is no difference in the specific gravity of the two silicate minerals. Absolutely proved, then, that the differentiation is not due to "gravitative settling." What then? What determines the order of these layers? The answer is *relative age of minerals.* The oldest silicate, the olivene, forms, (accurately speaking) *not the lowest layer,* but, considering both the horizontal and vertical sections together, the *core* of the dome-shaped intrusion, the next oldest silicate (pyroxene) the intermediate layer, and the latest silicate (feldspar) the outermost layer, next to the intruded schist. Not gravity but some other force has arranged these silicates in the order of their deposition, working from the periphery inward, or from the mass of the intrusion outward. Such a force is *gaseous tension,* and I submit the hypothesis that this is the force in question, working from the mass outward toward the periphery.[27]

[27] According to the gaseous-tension theory, differentiation would begin whenever the magma is released from external pressure higher than or balancing the highest gaseous-tension forces of the magma. The same unbalancing determines surgence or upward intrusion of the magma. We may imagine, and (from the known facts) believe, that magmas are thus kept inactive at a certain considerable depth. When the excess of pressure from without is replaced by excess of pressure from within (which change may be due to erosion lifting enough of the overlying pressure to turn the scale) then upward surgence, gaining strength as higher horizons are reached, takes place; and whenever a body of magma comes to rest the differentiating process becomes effective, for while the magma is in motion any differentiation will be lost through mechanical mixing.

An interesting testimonial to the inferred law that intrusion demands a greater pressure on the part of the magma than is exerted by the intruded rock is afforded by Fig. 92, a drawing which I made of an intrusion of a pegmatite dike into gneiss (both pre-Cambrian) in Georgetown, Colorado.[27a] The dike cuts across the laminæ of the gneiss, and penetrates the gneiss wall rock intricately, as shown in the figure. Isolated fragments of the gneiss, however, which are a foot or more long, are entirely inclosed in the pegmatite, and are not intruded. Such fragments, having the equal pressure of the pegmatite on all sides, have a resistance power equal to

[27a] *Professional Paper* 63, U. S. Geol. Surv., p. 178.

This hypothesis involves the assumption that the intruded magma was in a condition of gaseous tension. That is the condition which I have deduced in an earlier chapter (Chapter III) to explain the facts of intrusion. Through the gaseous tension of the magma, it was able to force its way upward, and shove up and aside the immense overburden of schists to assume its present position. Only when the initial processes of consolidation began in the magma dome did the gaseous tension begin to act selectively and thus produce magmatic differentiation; or, at least, only then with any efficiency. I imagine the process of solidifying of an element or mineral compound—such as olivene—in the magma as, under these ideal conditions, a relatively gradual one, with stages between complete fluidity and complete solidity; and that this change is marked by a gradual loss of gaseous tension. Under these conditions the higher tension of the residual part of the magma, not so far

that of the pegmatite, so that no intrusion was induced; but the gneiss of the wall rock evidently exerted a resistant pressure less than the impinging pressure of the pegmatite, with the result that it was intricately intruded by pegmatite tongues and veinlets. The lens-string type of these intrusions supports the theory I have advanced for larger lenses of pegmatite, quartz, or ores in schist (Chapter II, p. 94): for the figure proves that shearing in the direction of the long axes of the lenses, shredding apart an originally continuous vein (an explanation often advanced), is out of the question, for such movement would have affected the actually straight and unbroken line of the main veindike. Nearly every one of these lens strings starts away from the main veindike as an ordinary intrusive tongue, and these have not been rendered lenticular, probably because the rigid strength of the wall of the main pegmatite dike has prevented the crushing together of the gneiss walls under the external pressure; but away from this rigid wall the gneiss walls have closed in on the consolidating dikelets, separating them into lenses. A third lesson to be learned from the drawing is the entire lack of corrosion, absorption, or assimilation of the gneiss by the pegmatite, as shown by the sharp angles and knife edges of the gneiss inclusions. Therefore, the veinlets and lenses in the wall rock are not due to replacement, but entirely to intrusion—the thrusting aside of the gneiss by a greater force, as is shown by the curving of the gneissic laminæ around the local swelling of the pegmatite veindikelets, indicating on a small scale the same truth which the granitic intrusions at Georgetown (Fig. 40, Chapter III) and elsewhere demonstrate on a larger scale—that intrusion is accomplished by a forcible shoving aside.

advanced in the stages of consolidation, would push it upward and outward past the earlier-forming mineral or minerals, securing thereby a place or zone in the outer part of the intrusion, paralleling the contact, and by the same act repelling the earlier-forming mineral or minerals, which thereby become consolidated in the center, with the later-

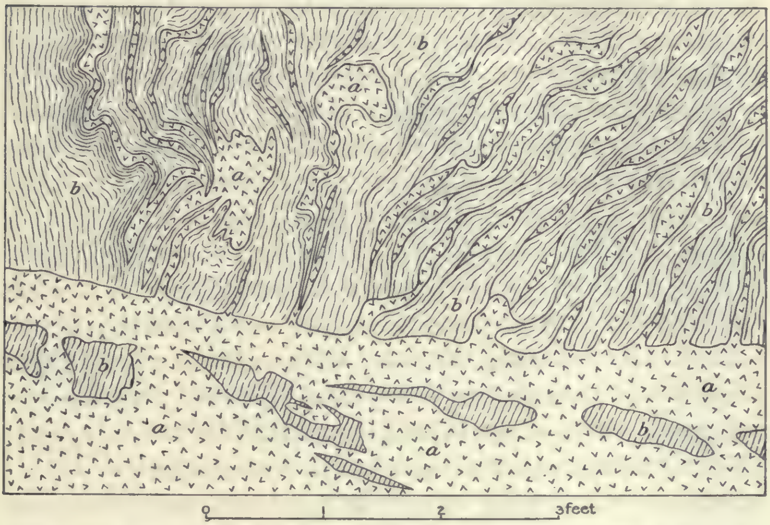


Fig. 92.—Georgetown, Colorado. Intrusion of gneiss by pegmatite. Illustrates theory of balanced pressure—the telluric or vapor-tension pressure of the pegmatite magma, which enables intrusion, and the opposing and resisting pressure of the gneiss, due to overlying load. The latter squeezes the pegmatite dikelets into lenses, where, after intrusion, the vapor-tension pressure diminishes during consolidation. The large included fragments are not penetrated by the pegmatite veindikelets, because, according to my theory, they are held in an equal pressure—that of the pegmatite magma—on all sides. Did this equal pressure also help to keep the fragments suspended in the fluid magma? *a*, Pegmatite; *b*, gneiss.

forming minerals on the outside. The gaseous tension would, of course, act strongly upward in the case of a dome, for the relief of pressure always exists in this direction; but it also exists in all directions away from the igneous mass toward the periphery. If the gaseous tension of the periphery-seeking portions of the intruded magma is powerful enough, it will cause marginal intrusions, especially as

peripheral dikes; and thus these dikes may represent many stages of the process of differentiation.

In the case of a dome, therefore, the gaseous tension will be up and laterally up, and the later (feldspathic-quartzose) fraction of a differentiated magma will form a cap fitting down (theoretically) over the top of the dome; in the case of a differentiated sill, the gaseous tension will be strongest upward, and the upper part of the sill will become more feldspathic-quartzose than the lower; in the case of a dike or relatively narrow irregular intrusive, the gaseous tension will be toward the walls, which will tend to become more feldspathic-quartzose than the center. Examples of the first case are, of course, these platinum-bearing domes of Russia[28]; of the second class, probably the main intrusive "sill" at Sudbury, Ontario, which is norite below, and granite-syenite above; and the third class is represented by certain dikes described by Hague,[29] Fouqué,[30] and others where the portions near the walls are more siliceous than the central parts. This order should apparently be the rule, especially for intrusions of some size. In certain dikes and other intrusions the reverse order has been observed, the more siliceous (and, therefore, the younger) part of the dike being in the center. A progressive crystallization due to the chilling effect of the walls is here suggested, the consolidation proceeding from outward in, but with the same order of mineral congelation. The temperature of the wall rock seems the deciding factor in determining which way the succession will run. When the wall rocks are little cooler than the magma (which will be the case more often in large intrusions), the typical rule of the feldspathic-

[28] Another example is Mount Johnson, Quebec, which (F. D. Adams, *Jour. of Geol.,* Vol. II, 1903, p. 225), is a volcanic neck. Its cross-section is nearly circular, about 3,000 feet in diameter, and shows a regular ringed arrangement, with essexite (about 48 per cent silica) in the center, and pulaskite (about 61 per cent silica) on the margin, and intermediate rock between.

[29] Monograph XX, U. S. Geol. Surv., p. 228.

[30] "Santorin et Ses Eruptions." Paris, 1879, p. 304.

quartzose rocks forming above, and on the periphery, should be found to hold good; so that the reverse should be found to be quantitatively unimportant.

It will be noted that these striking cases of rock differentiation in an intruded mass are mainly characteristic of the basic magmas, ranging in original average composition from diorite to gabbro or diabase. In the granite domes we do not note any zonal arrangement of this clear-cut nature. It is possible, indeed, that these granite domes may represent the upper, already differentiated, layer of originally intermediate-basic intrusive magma domes of vast dimensions, for in the regions where they occur there are in some cases not wanting other igneous sequences which indicate a general underlying intermediate magma. Extension of the conception might explain in the aggregate the derivation of the siliceous crust of the earth from the original magma, the lighter crust not originating by sinking of heavier materials, but by the upward-tending gaseous tension of the feldspathic-siliceous elements of the magma.[31]

It is further evident, from this theory of the differentiation of magmas through differential gaseous tension in the slow inceptive stages of consolidation, only begun upon the intrusion of the original, undifferentiated magma into the favorable temperature-pressure zone, that the time required for complete differentiation of a given intrusive mass or reservoir may be long or short, depending upon its size and the pressure-temperature conditions; and that, therefore, there is no standard time element in differentiation, although the time consumed is in any event fairly long. But it is understood why in Nevada, for example, three or more cycles of magma differentiation, as revealed by volcanic eruptions, may have taken place in the Tertiary,[32] while in the Rosita Hills, in Colorado, only two cycles are represented in the Tertiary.[33] This difference in rate of

[31] See Chapter IX, p. 404.
[32] See p. 230.
[33] See p. 556.

differentiation in magma reservoirs has been argued by Iddings.[34]

Reverting to the Ural deposits, the restriction of the chromite to the central dunite areas indicates a close association, from the beginning, between olivene and chromite, so that the molecular stiffening, which affected olivene first of all the silicates, was nearly simultaneous with a similar physical change affecting the chromite molecule. In spite of the fact that the chromite now occurs in perfect crystals in the olivene, it is not an untenable view, on the general principles above stated, that the chromite was the later crystallization; and that this explains the nests and streaks of chromite in the dunite. However, the fact that the chromite did not migrate beyond the principal olivene rock indicates that at least it solidifies at a temperature little short of that of olivene, which accounts for its practically exclusive association the world over, with olivene; and indicates that, like olivene, it loses its fluid condition in the magma very easily, so that it never migrates far. That it does, however, migrate within the indicated narrow limits is shown by its frequent occurrence on the periphery of peridotitic masses; and it is even known to occur as an independent intrusive.

Ilmenite is similarly closely allied as to conditions of fixation (and therefore of hypothetical vapor tension) with pyroxene, and, therefore, does not as a rule separate far from it.

Magnetite, however, apparently retains its vapor tension longer and, therefore, travels further: it is found in all the rocks of these Russian (Ural) centers. In fact, magnetite is a constituent (though "accessory") mineral, of nearly all igneous rocks, from pyroxenites to granites. Such a still fluid mineral, possessing the apparent high vapor tension peculiar to oxides like magnetite, hematite, cassiterite, and zircon, the metal sulphides, and the minerals of the fluorine-boron group, like tourmaline and topaz, can

[34] "The Problem of Volcanism," 1914, pp. 187, 259.

evidently pass through the magma at any stage, even after the latter is partly or completely solidified. Thus magnetite frequently not only groups itself along certain lines in the igneous rock, but penetrates the wall rock and forms masses in it. This accumulation of magnetite and hematite, by passage out from the magma, in the wall rock, is characteristic not only of basic magmas, but, to a less degree, of intermediate and even siliceous ones.

These iron oxides mark the beginning of a series of metallic mineral elements which have penetrated all classes of magmas. In this they differ, of course, not only from chromite, but also from platinum and nickel. Chromite, as above noted, is confined to the peridotites (of which group dunite is a variety). Platinum is also probably confined to the peridotites. Nickel occurs in connection with peridotites, pyroxenites, and even gabbros and diabase. (Fig. 93). None of these occur to any noteworthy degree in the siliceous igneous rocks.

Chromite is closely associated with (younger) platinum in many cases, and in some cases with diamonds; nickel is not, generally speaking, closely associated with chromite, but is frequently closely associated with platinum, as in Sudbury, and in the Rambler mine, in Wyoming. Nickel sulphide is frequently associated with copper sulphides also, as in the two districts above mentioned, and this leads as a transitional stage to the group of the copper deposits in basic rocks, without nickel sulphides. These copper deposits have a tendency to form sulphides high in copper and low in sulphur, as in the Kennecott mine, in Alaska, and this tendency ends in the deposition of primary native copper, as in Michigan. Such native copper deposits, as in Michigan, may contain arsenides of copper, nickel, and cobalt, and some native silver, and so are transitional into rich silver ores, as in districts like Cobalt, Ontario, which carry native silver, argentiferous cobalt arsenide, a little nickel, etc.; or Fredericktown, Missouri, which carries nickel-cobalt sulphides (linnaeite) as well as copper

(chalcopyrite) and galena. Close to this comes the Silver Islet mine, on the north shore of Lake Superior, carrying native silver and argentite, with galena, blende, and copper

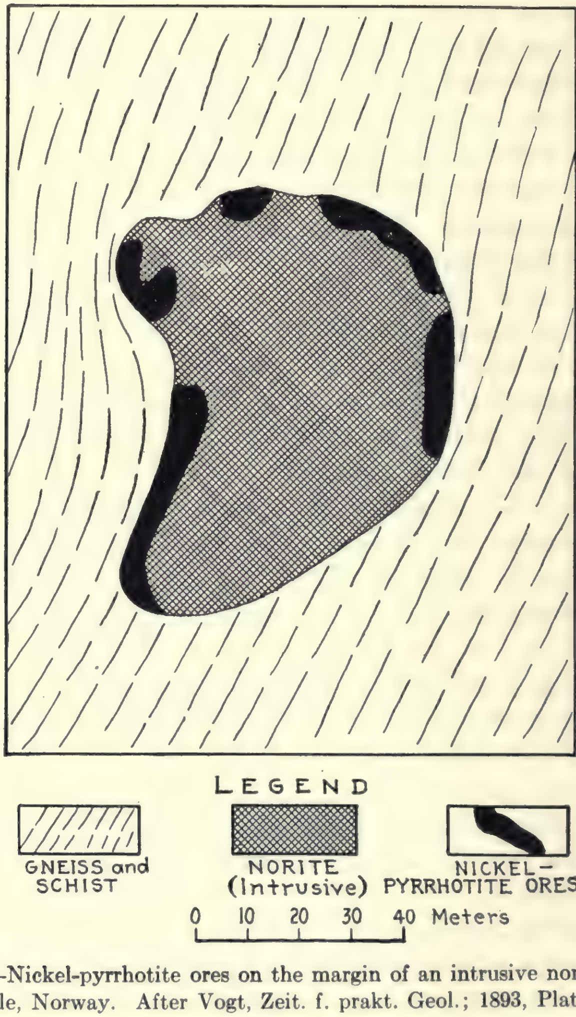


Fig. 93.—Nickel-pyrrhotite ores on the margin of an intrusive norite dome. Bamle, Norway. After Vogt, Zeit. f. prakt. Geol.; 1893, Plate VI.

pyrite, as well as nickel, cobalt, and arsenic. A step further than this, to still a probably allied form of ore deposit, is afforded by the lead-zinc deposits of the Missis-

sippi Valley. At Flat River, in Missouri, these ores contain some cobalt, and linnaeite has been identified there. All this series—chromium; platinum; nickel; copper; copper-nickel-and-cobalt arsenides and sulphides, and silver; blende and galena—is marked by generally scanty and inconspicuous gangue. The gangue where present is as much calcite as quartz; and certain stages of copper and silver deposition are marked by a striking scarcity of primary sulphur. Zeolites accompany many such copper deposits.

All these deposits, from chromium to galena, are derived from the basic magma in characteristically basic provinces; nevertheless, the evidence of magmatic gases is present in the ores at least of the copper-lead section of the series, as evidenced in gangue minerals in the Michigan copper mines containing boron (datolite) and fluorine (apophyllite), of fluorite in the Port Arthur mines of Lake Superior, which in general are of the Cobalt (Ontario) type, and of the great fluorite veins of the Mississippi Valley, associated often with peridotite dikes, and carrying galena and blende.

I wish now to cite an example of the magmatic differentiation of an ore from a siliceous magma.

The molybdenite deposits of the Renfrew mines, Renfrew County, Ontario, occur on the contact of considerable bodies of granitic pegmatite intrusive into limestone.[35] The molybdenite ores are mainly associated with abundant green pyroxene (diopside) and frequent scapolite, and also pyrite and pyrrhotite. "The molybdenite is most abundant where pyrite and pyrrhotite occur and is only sparingly present where these minerals are absent." In places the pyroxene rock contains a considerable proportion of microcline (the chief feldspar of the pegmatite) "so that all the intermediate types between a pyroxenic pegmatite and a feldspathic pyroxenite are present." This pyroxenic rim at the contact of the pegmatite and the limestones, as described, seems to me plainly a case of the modifying of a

[35] M. E. Wilson: Canada Department of Mines. Geol. Surv. Sum. Rep., 1919, Part E, pp. 37-41.

pegmatitic magma, before crystallization, by mixture of lime and magnesia from the probably dolomitic limestone. The quartz element of the pegmatite, by adding lime and magnesia, crystallized as diopside (lime-magnesia silicate); and

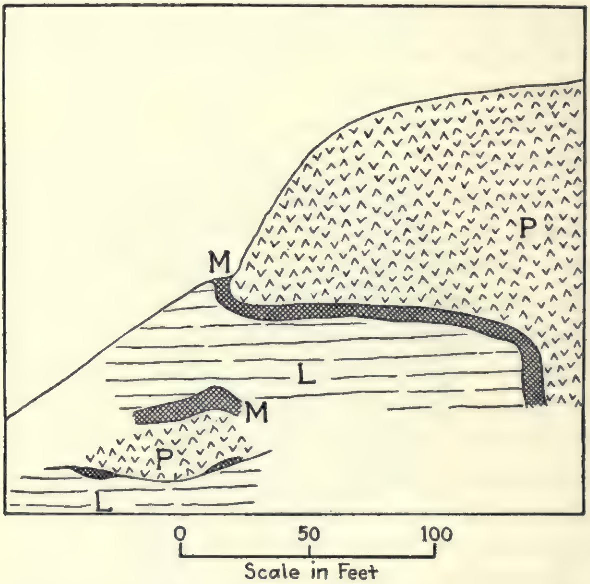


FIG. 94.—Hunt Molybdenite mine, Renfrew County, Ontario, Canada. Vertical cross-section. Slightly adapted from Canada Department of Mines, Geol. Surv. Report, 1919, Part E, Fig. 7. The molybdenite occurs on both upper and lower contacts of the pegmatite. It was a constituent of the pegmatite magma, as is shown by its frequently occurring in this region as one of the component primary minerals of the pegmatite. Its occurrence on both upper and lower contacts indicates migration from the pegmatite mass. Since its separation from the magma is a clear case of magmatic differentiation, we have here an example of magmatic differentiation due to (differential) gaseous tension. It is possible that this is the principal cause of magmatic differentiation in general. L, Limestone; P, pegmatite; M, molybdenite.

the albite (soda-alumina silicate) which occurs in the pegmatite, mixed with microcline, by mixture with the lime became scapolite (lime-soda-alumina silicate), while the microcline (potash-alumina silicate) crystallized as such, since there is no lime-potash-alumina silicate.

The chief occurrence of the sulphides on the margin, as described and figured (Fig. 94), leaves only one interpretation possible—that they escaped from the mass of the pegmatite to its margin under the force of their gaseous tension. *They occur below the pegmatite, where this has limestone below, and above the contact where it has limestone above, showing that they can neither have been due to ascending solutions, nor can they have settled out of the magma through the force of gravity. The direction of motion which these sulphides traveled was simply away from the consolidating pegmatite, whether up or down.* In this occurrence, as in many others, molybdenite often occurs as a constituent mineral of pegmatite, although it was probably the last mineral to crystallize (see p. 575); the critical conditions of consolidation of the magma, which determine whether the molybdenite is to crystallize throughout the magma, or is allowed to traverse it and segregate or differentiate itself to the magma margins, are evidently delicate (p. 101). The slower consolidation and more gradually falling temperature of a large mass of crystallizing pegmatite are probably favorable to the segregation of the molybdenite on the contacts; the more rapid crystallization of a narrow veindike of pegmatite, for the retention of the molybdenite as a constituent rock mineral. Nevertheless, the tendency toward the escape to the margins may be noted even in small pegmatitic veindikes, where the dual rôle of molybdenite as a primary constituent and a contact mineral (and yet in both cases of the same age and origin) may often be observed. The close association of the molybdenite with pyrite and pegmatite in the case I am citing indicates that this derivation and magmatic history is true also of the iron sulphides.

The case of molybdenite, so characteristic of the granitic pegmatites, is parallel as to its magmatic rôle with that of the chromite in ultra-basic rocks, which similarly sometimes occurs as an essential primary mineral of the rock, and is sometimes segregated into the zone of contact of the

igneous mass with an intruded rock. The point to fix in mind is that the molybdenite or chromite is probably always of the same magmatic age and origin, representing the last, or one of the last, of the magmatic minerals to crystallize; and the difference is in the degree of its magmatic segregation (due to the gaseous tension, and the consequent power of permeation and migration through the semiconsolidated magma). Also, where the molybdenite occurs, as it sometimes does, free from gangue, in crevices of granite or in the rock intruded by the granite, in the Canadian instances cited, it is still of the same magmatic age and stage as when it occurs as a primary constituent of pegmatite. These two metallic minerals, molybdenite, so typical of very siliceous and pegmatitic magmas, and chromite, so typical of very basic magmas, are most valuable guides to our comprehension of the origin and distribution of metallic ores, for they are both, in their respective magmas, clearly high-temperature sulphides, with a precipitation temperature very close to that of the rock silicates. Hence, one cannot mistake—at least one cannot possibly always mistake—their true magmatic character. But the other metallic sulphides, arsenides, etc., whose precipitation temperature is normally lower, are for that reason rarely trapped in the slowly crystallizing magma, and forced to play the evident rôle of a primary rock mineral. When they escape to the contact, they characteristically find it not yet cool enough for precipitation, and travel further, along available fissures, either up or laterally, or both.

It is mainly those metallic minerals of the lower zones of vein deposition (deposited at higher temperatures) which are occasionally and to a petty quantitative degree trapped in the igneous rocks (including the pegmatites), as an original constituent: gold occasionally, occasionally the copper sulphides, such as chalcopyrite, or bornite. If we study the schematic table on p. 611 (Chapter XIII) we shall see how true this is. In all the three lines of descent, it is the highest-temperature metallic minerals which are known

as sometimes primary rock minerals, and these also, to the great confusion of geological thought, appear on contacts, or even in veins (or veindikes), in the igneous rocks or in intruded rocks. Such is the case, for the basic sequence, for chromium, nickel, and platinum, all of which do so occur as primary rock constituents; it is the case, in the siliceous ore-sequence, for molybdenite, tin, and tungsten; and in the intermediate sequence, for molybdenite, tungsten, and gold. Going one step further down the scale of temperature, we recall that copper sulphides have been repeatedly reported as a primary constituent of pegmatites. But going still further down, sulphides of zinc, lead, and silver do not usually so occur. Their consolidation temperature is so low that rarely by any chance are they trapped as a constituent part of a rock or even pegmatite fabric.

Similarly, the true contact deposits (where by magmatic segregation the metallic oxides and sulphides—by virtue of their late crystallization, high gaseous tension, and power to permeate the consolidating magma—concentrate at the contacts, in the igneous rock or the wall rock) are also confined to the same high-temperature minerals: such, again, as chromium and nickel for the basic sequence, and molybdenite for the siliceous; also, I should infer on theoretical grounds, tungsten and tin. Yet most if not all of these may also so travel upward that the actual portion of the igneous rock in and near which they are precipitated does not represent the magma from which they emanated (which lies hidden at a greater depth), but is an earlier-cooled higher horizon of the same magma. Such is the case, for example, with the tungsten (scheelite) deposits of Inyo County, California.[36] Probably this upward migration is less marked in the case of nickel and chromium than in the high-temperature characteristic metals of the siliceous magmas, for the large amount of gaseous elements associated with the latter doubtless gives them an added mobil-

[36] ADOLF KNOPF: "Tungsten Deposits of Northwestern Inyo County, California," Bulletin 640-L, U. S. Geol. Surv., 1917, p. 240.

ity. But as for the lower-temperature minerals, like copper, zinc, lead, and silver, I doubt that the so-called contact deposits ever have been segregated from the igneous rock now exposed in the same plane; and believe that they are younger than such a co-exposed portion of the igneous rock, and have segregated or emanated from a portion of the magma at greater depth and migrated upward through openings in the solid rocks to the location where they have crystallized. This is a conclusion that all my observations indicate; and it is also the theoretical one, as we now see.

In magmatic ore deposits derived from intermediate and siliceous rocks the copper pyrite deposits, as I have noted, seem to have been deposited at about the same temperature range as the copper pyrite deposits derived from the basic rocks; and it is likely that from then on the series of metal sequences run a good deal side by side as to temperature conditions of formation:

Basic Magma.	Siliceous Magma.
Chromite	Tin
Ilmenite	Tungsten
Nickel Sulphide	Molybdenite
	Gold
Chalcopyrite—Native Copper Series	Chalcopyrite
Copper, Cobalt, Nickel, and Silver Arsenides—Native Silver	Argentiferous and Auriferous Pyrite and Arsenopyrite
Blende	Blende
Galena	Galena
	Silver Sulphantimonides, Sulpharsenides, and Sulphides

The parallelism of the two lines appears to lie in the following series, which seems to be similar and to form under much the same conditions of temperature and pressure: Chalcopyrite, arsenical ores, blende, and galena.

Gold is peculiar to the more siliceous series; cobalt (as well as nickel) to the basic series. There is the analogy, in both lines, of silver deposits of great value occurring in the "principal arsenic zone" which comes between the chalcopyrite zone and the blende zone; but there is, so far as I

know, no second silver zone, following the galena zone of the basic series, like the rich silver zone which follows the galena zone of the siliceous series. The lead-zinc ores of the Mississippi Valley, indeed, which I class with the basic series, are not argentiferous.

A bird's-eye view over the connected series of ore deposits descended or derived from basic magmas will show that while the earliest of them—chromite—shows little or no connection with the silica and with the gaseous components of all magmas, evidences of such a connection increase. Even the ilmenite, which comes next after the chromite, and which, as I pointed out above, has normally the same basic habit as the chromite, does also occur in the pegmatites associated with and derived from even the basic rocks, in company with quartz and such minerals as apatite and others, which are formed through the presence of phosphorus or chlorine or fluorine in the residual magma. Nickel sulphides show very little accompaniment of these telltale minerals, but do consort to a slight degree with quartz and calcite; while the chalcopyrite-native copper series is characteristically accompanied, even though scantily, by quartz and calcite, and minerals testifying to the presence of certain gaseous elements. The arsenide-silver group shows the gangues of calcite and quartz, as well as fluorite and other minerals, still more abundant (though never excessive), and the lead-zinc deposits show much association with fluorite as well as with barite. This association with quartz and other gangues betrays the origin of the segregation of ores of this basic-magma-derived series, as accomplished through the residual elements of the magma, and shows that the ores belong to this group of elements. The process of concentration, into ore deposits, of originally thinly dissolved metals in a basic magma is the same as it is in a siliceous magma; in both cases the ores are concentrated through their superior gaseous tension (volatility). Thus they remain fluid and capable of active migration after the rest of the magma has become inert and is crystallizing or

has crystallized. In the basic magma, as in the siliceous magma, the residual gaseous metal-bearing magma may contain also silica; and from this residual magma the different metals are deposited in the same sequence, and probably at the same temperature-pressure critical stages, as from the magma residual from siliceous rocks. The difference is that, since the basic magmas have a different selection and proportion of metallic elements from that of the siliceous magmas, the residual ore magmas have corresponding peculiarities. Another inevitable difference is that the residual magmas from basic rocks are quantitatively far less siliceous than are those derived from other igneous rocks, since the basic rocks, by their very definition, are poorer in silica and the gaseous elements. This does not militate against the richness of ores derived from basic magmas; indeed, it may even tend in the contrary direction, because there is not so much dilution and thinning, since these ore magmas are only slightly aqueous-gaseous and siliceous, being made up more largely of the metallic elements in sulphide solution. Even the sulphur in these basic ore-magma solutions is, like the other gaseous elements, far less in amount, and indeed does not suffice in many cases for the metals: so that the copper and silver, as in Michigan and Ontario, in part appear as very rich sulphides (poor in sulphur); and in part, the sulphur being exhausted, are deposited as the native metals.[37] This is not paralleled in the ore magmas residual from the siliceous magmas,

[37] A curious instance illustrative of this is reported from the copper district of Corocoro, in Bolivia, by Singewald and Berry ("Geology of the Corocoro Copper District, Bolivia," Johns Hopkins Press, 1922). The Corocoro district resembles the Lake Superior copper district in that the chief ores are of native copper. The ore occurs impregnating uptilted sandstone beds. Toward the surface some of the beds have chiefly copper sulphide (chalcocite), with copper arsenide (domeykite). Below 100 to 150 meters in these beds only native copper is found; but this and the chalcocite are held to be contemporaneous. The occurrence has the earmarks of a basic-magma-derived copper deposit, which coincides with the author's suggestion of derivation from an underlying diorite, although the known diorites outcrop 15 to 20 kilometers away.

which ordinarily have a superabundance of all the gaseous elements, including sulphur, as well as of silica.

The most siliceous magmas, on the other hand, separate vast quantities of siliceous-aqueous-gaseous residual magma, in which the originally thinly dissolved metals are efficiently extracted (more efficiently than in the case of the basic magmas, indeed, for the analysis of the basic rocks shows far more metallic content than do the siliceous rocks, for which reason it was long inferred that ore deposits of all kinds were closely dependent on basic igneous rocks), and from this abundant siliceous residual magma much quartz and other gangue material will be precipitated; so that in many cases wide veins of quartz will be formed, and deposits of solid sulphides will only form by a differentiation from the quartz of such a siliceous ore magma, at the critical period of consolidation of the latter. Therefore, in districts of ores derived from siliceous magmas, there will be much barren quartz, and much low-grade quartz, and much hunting for ore concentrations of high enough grade to form ore.

As for the origin of basic-magma provinces and siliceous-magma provinces, that is the problem of petrographic provinces, which, like the metallographic provinces, have their origin further back in the history of the earth's crust than we can now successfully pursue. In basic-magma provinces, of course, magmatic differentiation gives us all kinds of rocks, even to the siliceous rocks in small proportion; and in siliceous provinces differentiation gives us the basic rocks, although in small proportion; and in intermediate provinces, we get both basic and siliceous residual magmas in important quantities. In Canada (Lake Superior region), where the basic Keweenawan intrusive magmas were attended by deposits of nickel, cobalt, and copper, there was a far earlier (Algoman) period of intrusion of granites, attended by auriferous quartz veins and auriferous arsenopyrite veins; and apparently immediately preceding this, earlier basic intrusives, accompanied by nickel,

titaniferous and non-titaniferous magnetite, and chromite deposits.[38]

Such a major coupling of Algoman granites and immediately preceding Algoman basic intrusives, each with their characteristic ore deposits, suggests their derivation from a deeper common magma by some slow process of differentiation like that which performs sub-differentiation in the intruded basic magmas or in the intruded siliceous magmas; and still further sub-differentiation in the ore magmas, producing deposition of certain metals separately; and the still further differentiation, by which the consolidation of quartz-metal magma at a certain stage tends to separate metallic sulphides from quartz. A repeated process of splitting is apparent, of which the earliest stages become remotely ancient, shadowy, and vast, and ill-understood, and the latest become localized, performed in the crust which we know, by processes which we can trace; are more limited in geologic time necessary for completion, and result in such products as quartz veins, calcite and rhodochrosite, barite and fluorite veins, and in the deposits of the various metals which we seek.

In any igneous center, where rock differentiation has taken place, producing both basic and siliceous differentiation products (and that whether the original magma was basic or siliceous), we may judge the original character of the magma by the relative quantity of the basic and of the siliceous products. Such a test at once confirms our opinion of the original basic character of the magma at Sudbury and at Cobalt, for example, in spite of the minor granitic and even alaskitic dikes. And at Silver Peak it confirms the original magma as siliceous and granitic, in spite of the minor diabase differentiates which have formed dikes. There is a tendency for all differentiates from a common magma, whether very light or very dark resulting rocks, to be composed of much the same minerals in different

[38] Willet G. Miller and Cyril W. Knight: *Twenty-fourth Ann. Rep.*, Ontario Bureau of Mines, 1915, Part I, p. 245.

proportions. Thus in the dikes which I have described on Forty-Mile Creek, in Alaska[39] there is every possible gradation between very basic pyroxenites and alaskites, but the bulk of the rock is a hornblende granodiorite, which apparently represents the original magma: and a great variety of these rocks is produced by various combinations of hornblende, feldspar (chiefly orthoclase), and quartz, with a little pyroxene, and metallic minerals like magnetite, ilmenite, pyrrhotite, and pyrite. The same set of minerals in different proportion is found in all the rocks (p. 62). Similarly in the Ural occurrences, described by Duparc and Tikonowitch, although there is a great variety of differentiated rocks, the list of minerals in each indicates that the original magma was a pyroxene gabbro.

Once we come to recognize the essential points of difference between ore deposits derived from basic magmas and those derived from siliceous magmas, we can place them as easily as the corresponding pegmatites, whatever may be their nearest (often deceptive) association with igneous rocks. The ore deposit at Engels, in California, for example, consists chiefly of bornite and chalcopyrite, with some enargite, tetrahedrite and sphalerite, magnetite, ilmenite, and hematite. The bornite is four times as abundant as the chalcopyrite. Silicification is conspicuously absent and calcite is present in comparatively small amount. Here we have the earmarks—important copper sulphides low in sulphur, lack of silicification, and scanty calcite—which we have found characteristic of basic-magma-derived copper ores elsewhere; and, indeed, in this case the country rock is a norite (or diorite). Magnetite is here earlier in general than the bornite, as it should be by the rules I have tried to detect. As in the analogous case at Sudbury, there has been a difference of opinion among geologists as to the origin of these ores: H. W. Turner and A. F. Rogers held them to be of direct magmatic origin; and L. C. Graton and D. H. McLaughlin that they are pneumatolytic and

[39] *Eighteenth Ann. Rep.*, U. S. Geol. Surv., p. 233.

hydrothermal. This seems to be a matter of words, and both views may be right. Such a verdict reminds me of the Irishman who was asked to umpire a dispute between an American and an Englishman over the pronunciation of the word *either*. The former claimed it was *eether* and the latter *eyther*. "It's naything," said the Irishman; "it's ayther." It is magmatic, I should suspect; and I should say that all magmas are pneumatolytic and hydrothermal—and some much more so than others.

On the other hand, the gold veins of Victoria, Australia, are associated with large intrusions of granodiorite or quartz monzonite, with dikes of quartz-feldspar porphyries (alaskites), of diorite and gabbro, and narrow hornblende and biotite dikes (lamprophyres) and basalt porphyry. The relative bulk of the different intrusions, as described, however, as well as the mineral composition—biotite, feldspar, and quartz, with some hornblende—which runs through all, indicates a differentiated intermediate-siliceous magma (granodiorite to quartz monzonite). The veins are of quartz, of the type which I denominate as intrusive, and carry less than 2 per cent of various sulphide minerals and gold. The quartz veins are most commonly "related to lamprophyre and diorite porphyry dikes, but some are associated with granodiorite intrusions and quartz porphyry dikes and rarely with rocks of basaltic composition."[40] This frequent association with basic dikes cannot, however, lead us astray for a minute; for the type of veins is a typical siliceous end-product from an intermediate-siliceous magma (quartz monzonite); and its juxtaposition with basic dikes is plainly fortuitous, unless at times there may be some coupling on account of vein and dike being complementary—siliceous and basic extremes of differentiation.

Some further distinction between basic-magma-derived ore magmas and siliceous-magma-derived ore magmas will be discovered in the chemical nature of the solutions re-

[40] N. R. Junner: "Gold Occurrences of Victoria, Australia," *Econ. Geol.*, Vol. XVI, No. 2, March, 1921, p. 83.

sidual from the crystallization out of the metallic and gangue minerals. In the case of the siliceous-magma-derived ore magmas these residual solutions are plainly not only highly siliceous, but alkaline. At Tonopah, for example, the wall rocks near the veins are silicified by these residual solutions; and, moreover, there is the development of sericite and of potash feldspar, or adularia, the latter formed at the expense of original soda-lime feldspars. "The conclusion is drawn that the mineralizing waters were charged with an excess of silica, and probably of potash; that they also contained carbonic acid and sulphur, with some chlorine and fluorine; but that they were noticeably deficient in iron."[41]

It follows from this siliceous-alkaline nature of the siliceous-magma-derived ore magmas that their residual solution will alter the wall rocks more markedly in proportion as these diverge from the siliceous extreme type, and that basic rocks will be especially attacked.

In the Victoria, Australia, case just cited, for example, dioritic rocks near the veins are bleached and altered, for a width up to two or three feet, to a product composed of quartz, albite (soda feldspar), sericite, and ankerite (iron-magnesia carbonate). The dark ferrosilicate minerals (hornblende, biotite, augite) disappear entirely, and the soda-lime feldspars are altered to soda feldspars or sericite.[42] In this case also the solutions were plainly siliceous-alkaline, though with more soda in comparison with potash than at Tonopah. It may be noted in passing that the Victoria veins are of the deep gold-quartz type, and the Tonopah veins are of the shallow type associated with volcanic rocks; and that soda feldspar (albite) seems more characteristic of deep ore deposits, and potash feldspar (adularia) of shallow ones (see p. 302).

At Silver Peak, where the auriferous quartz veins are siliceous-magma derived, the wall rocks are alaskite and

[41] *Professional Paper* 42, U. S. Geol. Surv., p. 22.
[42] *Econ. Geol.,* Vol. XVI, No. 2, March, 1921, p. 87.

diorite.[43] The alaskite is quite fresh, its feldspars (orthoclase and albite) are unchanged except for some slight magmatic alteration of the orthoclase to muscovite. The fact that the quartz veins are transitional into alaskite explains the lack of altering effect of the consanguineous ore solutions on the rock. But the diorite, which is of almost the same age as the quartz veins, but barely later (it interrupts the ore deposition, and is succeeded by its final stage) "is generally entirely decomposed and is now an aggregate of secondary products, chiefly chlorite, calcite, pyrite, quartz,

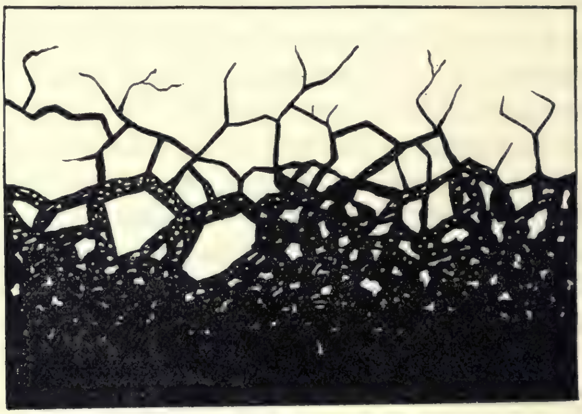


Fig. 95.—Intrusive contact of massive sulphides (of iron, nickel, copper) into older igneous rock (norite). Shows included fragments of wall rock, held suspended and isolated in ore magma. Black represents sulphide; white, norite. Scale about 4 feet to 1 inch. Creighton mine, Sudbury, Ontario, Canada. After E. Howe.

sericite, zeolites, etc." The original hornblende and soda-lime feldspars of this rock have been destroyed. Similarly, in the wall rocks of the gold-quartz veins of the Southern Appalachian district, the basic wall rocks (amphibolite) have been much altered, with the development in places of dark mica (see p. 599), while the alteration of granite is usually slight.[44] Widespread alteration of wall rocks for some distance away from the veins in dis-

[43] Spurr: *Professional Paper* 55, U. S. Geol. Surv, pp. 44, 114.

[44] Lindgren: "Mineral Deposits," 1919, p. 675.

tricts of siliceous-magma ore deposition, to chlorite, calcite, and pyrite, or extensive silicification, is frequent.

On the other hand, consider again the effects of the basic-magma-derived ore magma. At Sudbury, there is some little quartz and calcite with the sulphides: these sulphides not only pierce the country rocks by a process of intrusion —as I take it (Fig. 95)—but replace them, appearing spotwise in the intruded rock after the manner I have described in igneous rocks for those minerals which have the power of penetrating solid rocks by virtue of their gaseous tension. Nevertheless, the country rock is little altered, even next to the ore, whether the rock be basic or siliceous. The hypersthene of the norites, and the feldspar of the granites, are alike generally fresh.[45] Surely this indicates a striking relative lack of the mineralizers, of fluorine or chlorine, excess water and sulphur; in fact, a relatively dry, though fluid, sulphide magma, like the chalcopyrite-blende magma of the Mandy, in Manitoba, or the Potosi ore (pp. 116, 321).

Many of these copper-sulphide magmas derived from basic rock magmas do, however, alter the basic wall rock, and so demonstrate that the magma was more aqueous than at Sudbury and the Mandy. Yet even in these there may be little evidence of much silica or alkalies, or of gases. At Kennecott, in Alaska, for example, the ore, where it occurs in limestone, is unattended by gangue minerals or silicification,[46] but in the basic rock (altered basaltic rock) there has been the development of zeolites—laumontite and thomsonite (hydrous lime-alumina silicate and hydrous soda-lime-alumina silicate), epidote (hydrous lime-iron-alumina silicate), serpentine (hydrous magnesia silicate), chlorite (hydrous iron-magnesia-alumina silicate), opal

[45] Report of Ontario Nickel Commission, pp. 145, 149, 151, 167, 169. But Alfred Wandke and Robert Hoffman, in a paper before the Society of Economic Geologists (Ann Arbor meeting, Dec., 1922), showed that the granite walls of some of the sulphide veins at Sudbury are distinctly altered and replaced by hornblende, biotite, albite, and quartz.

[46] A. H. Bateman and D. H. McLaughlin: *Econ. Geol.,* Vol. XV, No. 1, Jan.-Feb., 1920, p. 34.

(hydrous silica), chalcedony, and quartz. These minerals seem to have resulted from the rearrangement of the materials of the basic rocks under the influence of the water exhaled from the ore magma, without any addition of material other than this water. In the case of a siliceous-magma-derived ore magma, such a deposition of copper in limestone would have probably been attended with the deposition of much silica and the formation of lime silicates. But it does not seem that these basic-magma-derived ore magmas are siliceous. Indeed, in the copper mines of Michigan I have noted evidence that lime was in excess, and has replaced quartz.[47] All copper deposits and other metallic mineral deposits accompanied by the formation of lime silicates from limestones are, therefore, probably from siliceous or intermediate ore magmas, which were derived from siliceous or intermediate rock magmas.

The intrusion by a siliceous-magma-derived ore magma of a basic rock is, of course, a possible instance; and in this case we need not be deceived by the character of the wall rock, for the peculiarities of the ore magma will stamp its origin. Such seems to be the case at Juneau, Alaska,[48] where dioritic rocks are pierced by gold-quartz veins. The ore is free gold with pyrite, pyrrhotite, chalcopyrite, arsenopyrite, zinc-blende, and galena, the gangue being mainly quartz with some calcite or dolomite, and a little tourmaline. The original diorite, which contained albite-oligoclase, microperthite, hornblende, and biotite, has altered to albite, quartz, calcite, muscovite, biotite, epidote, zoisite, pyrite, etc. The changes show silicification and the addition of alkalies, both sodium and potassium. Residual ore-magma solutions like those which were residual from the gold-quartz veins of California and Australia are indicated. The siliceous gangue; the gold mineralization; the alteration of the wall rock to a more siliceous-alkaline composition; the tourmaline, indicating active gaseous

[47] J. E. Spurr: *Eng. and Min. Jour.*, Aug. 21, 1920, p. 356.

[48] A. C. Spencer: Bulletin 287, U. S. Geol. Surv.

components of the ore magma: all mark this ore magma as siliceous-magma derived (intermediate-siliceous), in spite of the diorite wall rocks. The biotite, which is an alteration mineral of the diorite, is evidently due to the influence of fluorine on the ferruginous primary minerals, and hence should be relatively more common as an alteration product of basic wall rocks than of siliceous rocks.

In general, in many attempts which have been made to classify ore deposits, I feel that too much significance has been attached to certain gangue minerals, and indeed to gangue minerals in general. For example, to me the gold-quartz veins of the Treadwell, in Alaska; of California; of Silver Peak, in Nevada; of Canada; of the Appalachians; and of Australia are all of the same magmatic type, close to the granitic magma, and frequently showing (as they do in Nevada, Canada, the Appalachians, and Australia) transitional phases to pegmatites. All have the same type of auriferous quartz, with free gold and sparse, slightly subsequent metallic sulphides. The formation of albite as a vein or wall mineral is typical of the Treadwell, of California, and of Australia at least; but in Silver Peak, which is, in my opinion, indubitably of the California type, though possibly representing a somewhat greater depth than in California, there is no vein albite. But in Australia, where albite does occur, the alteration of the wall rock nevertheless results in a net increase of potash (as at Silver Peak) while soda is in places markedly reduced.[49] A classification based on albite is, therefore, I think, misleading, as would be, I think, a broad classification based on the presence or absence of a certain amount of tourmaline as gangue, or in the wall rock. All my studies of rock magmas and ore magmas indicate to me that the proportion and nature of the volatile, gaseous components in these magmas is extremely variable, and that a very limited amount (if any) is sufficient to furnish a solvent or carrier for the metallic sulphides, which are the "essential" ingredients of an ore magma, and

[49] *Econ. Geol.,* Vol. XVI, No. 2, March, 1921, p. 89.

which themselves, I infer, possess in the magma stage an independently high or long-sustained fluidity; that from these ore magmas, *whatever may be their variable proportion of gaseous components,* the metallic minerals are deposited in the same order and under much the same conditions of temperature and pressure; so that the excess proportion of the gaseous elements, which may or may not be present in such way as to form tourmaline and similar minerals, serves for little more than "fireworks," and does not affect the nature of the vein, or serve as a criterion of it, of the first degree of magnitude. An exception must, perhaps, be made for extremes. With extreme abundance of these ingredients, we shall have a highly gaseous ore magma, which I have called a superpegmatitic magma. and unquestionably such a magma has excellent powers of concentration and selection for certain metals; and seems, for example, to be essential to the solution, carriage, and deposition of tin. With this and some other exceptions, we can, I think, pretty nearly overlook the finer distinctions, and disregard the varying evidence of different amounts of water and other high-gaseous components in the typical ore magma.

To complete my discussion, I should like to be able to cite an example of basic-magma-derived ore deposits entirely in siliceous wall rocks. While nothing quite typical occurs to me, I might cite the Ferris-Haggerty orebody, in the Encampment district, Wyoming, where the ores are associated with a differentiated basic magma. The ore minerals are chiefly chalcocite (perhaps largely secondary) and chalcopyrite, with a schist hanging wall and a quartzite footwall. This has been studied and described by Dr. A. C. Spencer and myself.[50] There is no gangue, and the wall rocks show so little trace of change that it was concluded that even the schist was not penetrated by the mineralizing solutions, indicating a relatively dry or aplitic ore magma.

[50] *Professional Paper* 25, U. S. Geol. Surv., p. 74.

The ore incloses many angular fragments of quartzite held isolated and unsupported, showing (to me) the intrusive nature of the sulphides (Fig. 96). Compare this illustration with that of the vein at Sudbury shown in Fig. 95 (p. 596).

I have discussed in this chapter, as the two extremes, first the splitting into successively more specialized sub-

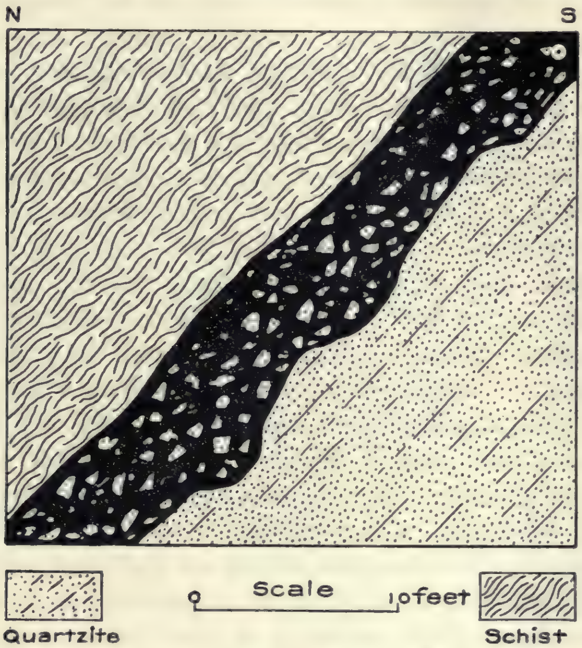


FIG. 96.—Isolated inclusions of country rock (all quartzite) in massive sulphide (chalcopyrite-chalcocite) ore. Solid black represents massive sulphide ore. Encampment district, Wyoming; Ferris-Haggerty mine. From Professional Paper 25, U. S. Geol. Surv.; Fig. 23, p. 80.

magmas, of an original alkaline-siliceous rock magma; and second, an originally basic magma. What of the third case, an intermediate original magma? Evidently this will, under the same conditions, undergo the same process of subdividing, under the influence of developing tendencies of crystallization and differences of fluidity (including gaseous tension) of the components, and will develop pegmatitic rock magmas and ore magmas. Experience indicates,

however, that these intermediate original magmas will not represent a notable concentration of the elements so characteristic of basic magmas, such as chromium, nickel, and platinum. On the other hand, consideration of known occurrences makes it seem unlikely also that they will contain a notable concentration of those elements so characteristic of siliceous magmas, such as tin, tungsten, and molybdenum. They will evidently contain the metallic elements which I have shown to be common to both extremes: copper, silver, lead, and zinc, together with arsenic and antimony. Since there is a graded and continuous transition between very basic and very siliceous rocks, there is no hard and fast line in this ruling, which permits, as will be seen, many combinations; but in general it should hold good, and should explain many mineral groupings. Similarly, in the case of these intermediate-magma-derived ore magmas, the amount of gangue, and the evidence of the excess of volatile components in forming characteristic gangue minerals, and in the nature and degree of alteration of the wall rock, should also be of an intermediate nature.

I have pointed out that the typical siliceous-magma-derived ore magma is in considerable part siliceous-alkaline, as shown by its alteration effects on wall rock, while the typical basic-magma-derived ore magma is not to any important degree either siliceous or alkaline, as is shown by the lack of alteration effects. The latter may even not be noticeably aqueous, as at Sudbury, Encampment, and other places, or it may contain a noticeable amount of water, which has the curious tendency to reconstruct basic wall rocks and develop hydrous silicates therein, such as are not characteristic of siliceous-magma-derived ore magmas. Plainly, except in the case of those metals peculiar to siliceous magmas, the excess of water, of other gases, of silica and the alkalies, is not essential to concentration and maintenance of fluidity of the ore magmas, which seem to be fluid largely because of the fluidity and elevated gaseous tension of the metallic sulphides themselves. The same fact

is shown by the process of splitting of siliceous ore magmas, such as those which have formed quartz veins, whereby the metallic sulphide magma is often left over from the consolidation of the quartz, and crystallizes later in the crevices of the quartz, or penetrates the wall rock.

CHAPTER XIII

The Three Main Lines of Descent for Ore Deposits

This chapter calls attention to the fact that the ore magmas derived from the most siliceous mother magma show the rough sequence: tin, tungsten, copper, zinc, lead, silver; but that gold is practically absent; and concludes that gold may be characteristic of intermediate rather than siliceous or basic magmas. This gives us three chief lines of ore descent, to all of which the sequence copper, (silver), zinc, lead, (silver), is common.

Besides occurring in a definite principal zone, metals like nickel, gold, and silver recur at higher zones, or under lesser temperature-pressure conditions; and in these cases usually in combination with arsenic or antimony, and to a less degree with tellurium and selenium. This defines a group of mobile metals, which are not themselves static as to temperature-pressure conditions for deposition; and which are, moreover, great carriers of the other more static-tending minerals. The effect of mobile metals as carriers is probably more universally important than that of gaseous elements like fluorine, boron, or water.

The basic-magma-derived ore magma is found to be calcic, and poor in water and gases; the siliceous-magma-derived ore magma, to be siliceous, and rich in water and gases.

DECIDEDLY BASIC MAGMAS, such as those from which peridotites form, have segregated almost exclusively unto themselves, from some grander, more primeval magma (which is only inductively visualized by the evidences of consanguinity and the gradations which run through all magmas), chromium and nickel. The opposites or complements of these basic magmas, the siliceous magmas, such as those from which granites and alaskites have formed, have also segregated exclusively unto themselves tin and tungsten. In considering the further line of descent of ore deposits from basic magmas, or the succession of metal deposition with decreasing temperature

and pressure, I have shown that gold has not been concentrated in these basic magmas, but that the main succession is: chromium, nickel, copper, silver, zinc, and lead. I have also noted the curious circumstance that gold, although it does not occur in connection with the very basic magmas, and is, therefore, confined to the relatively siliceous magmas, is not at all an associate, broadly speaking, of the tin deposits, although the deep-seated gold-quartz veins have formed at much the same temperature as the tin veins, as shown by the close relation of both to immediately earlier pegmatites. This lack of gold is, moreover, shown in the whole line of descent of the succession of metal deposition which begins with tin. This succession from the very siliceous magma is, broadly, tin, tungsten, copper, zinc, lead, and silver; partly like (in the broadest sense) the succession from the very basic magma, if you begin with copper and end with lead.

As I have not sketched out the tin succession, as a separate picture, I will briefly refer to some of the salient facts. In Cornwall there is the succession tin, tungsten, copper, zinc, and lead, the lead being argentiferous.[1] Gold occurs rather rarely and is not of commercial significance.[2]

In Tasmania, there is the same general succession,[3] the three main classes of mineral deposits being tin-tungsten veins, copper veins, and silver-lead veins, the latter also containing zinc, and carrying gold in commercial quantities, as well as silver. Some gold also occurs in the tin-tungsten veins. The temperature relations of the different zones are apparently the same as those I have repeatedly described in the foregoing pages for vein sequences in districts that are not tin-bearing. The tin and tungsten are associated with

[1] *Econ. Geol.*, July-Aug., 1908: "Geological Aspect of the Lodes of Cornwall."

[2] J. H. Collins: "The Precious Metals in the West of England." Journal of the Royal Institute of Cornwall, No. L.

[3] A. McIntosh Reid: Tasmania Department of Mines, Geol. Surv. Bulletin 30, pp. 43-44.

quartz, fluorspar, topaz, and tourmaline. The copper ores carry also, besides subordinate lead and zinc, plentiful pyrrhotite and hematite, and some arsenopyrite and magnetite. Gangue minerals are actinolite, epidote, quartz siderite, and calcite, indicating the temperature of the copper stage as that of the formation of hornblende and of quartz and calcite, quite as at Matehuala and other type-localities of copper ores not associated with tin. The lead-silver deposits have a quartz-siderite gangue, again quite in accord with temperature conditions for galena ores in non-tin-bearing districts. In some cases, in the tin-tungsten veins, cassiterite and wolframite crystallized out first, followed by quartz and arsenopyrite;[4] so that arsenopyrite has the same relation to the earlier tin-tungsten veins as it has to the earlier gold-quartz veins at Silver Peak, in Nevada, and Herb Lake, in Manitoba. Moreover, tourmaline occurs in these tungsten lodes, which contain little or no gold, just as it does in the Herb Lake gold-quartz lodes (see p. 105), which contain in places rich gold, but no tin or tungsten. This shows the distinct genealogy of the ore magmas in these two type cases.

The tin deposits of the Seward Peninsula, Alaska,[5] contain also wolframite, and as well arsenopyrite, chalcopyrite, galena, and blende. They are not reported, however, to contain gold, although this is a region of rich gold occurrences, derived from the deep-seated gold-quartz vein type.

All these tin-sequence occurrences are in connection with intrusive granite.

In Bolivia,[6] the tin veins, which are quantitatively very important, have formed in depths and at high temperatures, and later rich silver-bearing veins were formed at moderate depths. All are connected with later Tertiary porphyries and with granites whose age is uncertain. The tin veins in the granite, which are closely connected with tungsten

[4] A. McIntosh Reid: *Op. cit.*, p. 48.
[5] A. Knopf: Bulletin 358, U. S. Geol. Surv., 1908.
[6] W. Myron Davy: *Econ. Geol.*, Vol. XV, No. 6, p. 467.

veins,[7] carry, as usual, tourmaline; and in the tin veins within the granite this is the chief accompanying mineral[8]; but in the intruded sediments, and, therefore, inferentially in a cooler deposition zone, there is, in addition, pyrrhotite, pyrite, arsenopyrite, chalcopyrite, and quartz. Another class of tin-bearing veins are associated not with the granite but with intrusive porphyries and even volcanic rocks; these contain no tourmaline, topaz, or pyrrhotite, but do contain abundant arsenical and antimonial sulphides, such as jamesonite, arsenopyrite, and complex sulphides, including tin in the form of stannite (sulphide of tin, copper, iron, and zinc). Silver, which is very rich and important commercially, occurs in the form of tetrahedrite.[9]

Now, this Bolivian tin occurrence differs chiefly and most strikingly from the Cornwall and Tasmania type occurrences, mentioned above, in that the last stage is the rich silver-bearing stage, where silver occurs in concentrated form, associated with arsenical and antimonial compounds, and is, therefore, the same silver stage which normally overlies the main galena stage, and is commonly and strikingly shown in many mining districts not belonging to or near a tin district, such as Aspen and Ouray, in Colorado (see pp. 288, 680), or Velardeña, in Mexico (p. 271). Gold is mentioned as occurring in the Bolivian deposits, but apparently is quite as much of a rarity as in Cornwall. The full development of the silver sulphide stage in Bolivia does not in my opinion constitute this district an anomaly, for this is only a slightly more advanced stage (as seen in vein sequences in hundreds or thousands of localities in non-stanniferous mineral districts) from the argentiferous galena stage, which stage is well developed in Cornwall, in Tasmania, and elsewhere, as the last-displayed stage of the

[7] F. L. Hess: "Political and Commercial Geology," 1921, p. 150. "The [tungsten] veins are closely connected with the tin deposits, and in many veins tin and tungsten are associated, but many tungsten deposits contain little or no tin."

[8] W. Myron Davy: *Econ. Geol.*, Vol. XV., No. 6, p. 471.

[9] W. Myron Davy: *Op. cit.*, p. 473.

sequence in which the tin stage is the first. The intermediate stages are not so well developed in Bolivia as in the two type-localities just mentioned, although that they do exist is shown by the presence of copper, lead, and zinc sulphides, while the sequence of metallic-sulphide deposition conforms more or less to the usual rule. The distinctiveness of the Bolivian tin district, consisting first of its showing the principal silver zone, and second in its suppression to a large degree of the principal copper, zinc, and lead zones shown in the more regular and uninterrupted sequences of Cornwall and Tasmania, suggests to me two periods of intrusion and vein formation. The tin-tourmaline-tungsten lodes probably represent an earlier deep deposition zone; and the tin-bearing silver lodes a later and shallower ore deposition, connected probably with a new phase of the intrusion and a fresh supply of the differentiated ore magma, which originally will have been of the same nature as the ore magma of the earlier vein stage. This is also indicated by the association of the earlier stage with granites, the later with intrusive porphyries and volcanic rocks. Plainly, the later stage is a relatively superficial one, recalling the fact that tin ores do occur sometimes in rhyolite, where they have formed close to the surface; and the mineralogy of the tin-silver ores of this later stage suggests plainly the "telescoping" of normally successively overlying stages of the ore magma. I have earlier described this process (Chapter VI). During periods of volcanic activity, when rocks are highly heated almost up to the surface, the ore magma arrives, on its upward passage, quite near the surface without having encountered a temperature low enough to precipitate any part of it: but quite close to the surface, the chilling is so sudden that to a considerable degree all the components of the ore magma have crystallized together. On the basis of this reasoning, I would suspect that the granite is older than late Tertiary.

While the tin-silver stage, at least, of the Bolivia tin veins is, as above mentioned, late Tertiary, the tin vein-

sequence of Tasmania is Devonian, and that of Cornwall marks the division between the Carboniferous and the Triassic. The ores of the Seward Peninsula are post-Carboniferous. In the Malay States, the tin deposits are post-Triassic. These few instances will show that we have to do with a constant type of ore magma which has occurred at various places at various stages of the world's history, but always in connection with granitic rocks.

I have gone into this tin-vein association with a very siliceous magma, and discussed the tin vein-sequence, largely to show that except for the tin and tungsten of the earlier stages of the sequence, it runs through similar copper, silver, zinc, and lead stages as the other ore sequences, which spring respectively from the very basic magmas and from the magmas whence spring the gold-quartz veins. This brings out the conviction that as the tin-sequence ore magma differs from the gold-quartz ore magma, the rock magmas whence they are derived must somehow fundamentally differ. It is easy to see that this is the case between the tin-tungsten, silver sequence and the chromium-nickel, lead sequence, because there it is patent that the opposing sequences spring from the two opposite extremes of magma types. But such a magma difference is not so apparent in the case of the gold-quartz sequence, which does not, it is true, occur as a derivative of very basic magmas, but which, on the other hand, appears frequently as an apparent derivation from siliceous or granitic magmas.

Gold-bearing ores are a usual type—far more common than the extreme types above mentioned. While nickel ores are found only here and there in the earth's crust, and the same exclusiveness and erraticness marks tin deposits, gold deposits are widely found, and in connection with a very considerable range of rocks, from diorite to granite. And this fact, and this exclusion of gold (broadly speaking) from both the nickel and (actually though not so categorically) from the tin districts, leads to the thought whether this actual range for gold does not indeed define a special

range of magma in which gold is concentrated, and that it is concentrated in the intermediate magmas, just as nickel is in the very basic and tin in the very siliceous. This tentative hypothesis is quite fixed as a conclusion in my mind, as relates to the very basic magmas; but the exclusion from the very siliceous magmas is contrary to my previous conclusions.[10] In 1902, I endeavored to show, and I think did show, that the previously widely held opinion that gold was preferentially or exclusively associated with basic igneous rocks was an error; and I concluded that "an overwhelming majority of gold-quartz veins occur in connection with rocks of the dioritic and granitic families." Such a conclusion I have never found reason to change; but now I am inclined to suspect that the intermediate-siliceous magmas there defined as the mother of the gold-quartz ores should not include the very siliceous magmas. In saying this, I am speaking of magma provinces in the broad way, not of local occurrences of igneous rocks. Even the very basic magma provinces, in which chromium and nickel occur, show limited amounts of more siliceous rocks, and indeed granites and granite pegmatites, as a result of their differentiation[11]; and perhaps (which I do not know) the siliceous granitic provinces in which tin occurs may contain limited amounts of diabase as a differentiation product. The intermediate magmas most certainly by differentiation produce granites and alaskites, and diabase as well. The gold-quartz veins represent the final siliceous fraction of the magmas; but it may be that it is from the siliceous differentiation phases of major intermediate magmas that they are derived. When one considers the great granodioritic magma of California, with which the gold of that region is associated, and the great fundamental monzonitic or granodioritic magma of the Cordilleran states and Mexico, on which the gold deposits, and the ores of the

[10] J. E. Spurr: *Trans.* A. I. M. E., Feb.-May, 1902, p. 34.

[11] As in Sudbury (see p. 567); see also John A. Dresser: *Trans.* Roy. Soc. Can., Third Sec., 1920, Vol. XIV, pp. 8, 9.

gold-quartz vein sequence, with which I have dealt almost exclusively in my previous discussions, are intimately dependent, it seems a permissible hypothesis that the gold, excluded both from the very basic and the very siliceous specialized regional magmas, remains in the wide range of intermediate magmas which may be grouped as dioritic and granitic, or granodioritic. The gold-quartz vein sequence is the one which I have invariably given in my list of vein stages previous to Chapter XII, and I would simplify it as: (molybdenum, tungsten) gold, copper, zinc, lead, silver.

Therefore, we may construct the sequence of the three principal lines of ore-deposit descent somewhat as follows:

Basic Magma	Intermediate Magma	Siliceous Magma
Chromium	Molybdenum	Molybdenum
Platinum	Tungsten	Tin
Nickel	Gold	Tungsten
	Copper	
	(Silver)	
	Zinc	
	Lead	
	(Silver) (See p. 588)	

It is natural, from the foregoing explanations and assumptions, that the distinction between the intermediate-magma types and the siliceous-magma types should not be so clear cut as between the intermediate and the basic types. For example, I have included tungsten in both the intermediate and the siliceous sequences. It certainly belongs in both, for the tungsten-bearing areas are equally characteristic of the great intermediate-magma provinces—as in Colorado, Nevada, and California, for example—as they are of the great tin-bearing fields, like those of Cornwall, Australasia, and Bolivia. Gold is probably later than tungsten, according to my general impression, and according to some notes of Hess.[12] Molybdenite is another mineral that is characteristic of both these sequences; but possibly it has a preference for the intermediate side, as the tungsten perhaps has for the siliceous side. Gold also, as

[12] Bulletin 652, U. S. Geol. Surv., p. 46.

we have seen, is not absolutely excluded from the tin-sequence deposits, although it rarely occurs in commercial quantity. Indeed, on a very small scale, we shall find representatives of each of these key metals of the diverse lines sometimes where we least expect; for example, rare nickel and cobalt are reported from the tin ores of Cornwall. This simply indicates the ultimate consanguinity of all magmas.[13]

[13] The occurrence of gold in connection with the siliceous differentiation product of a basic magma is illustrated in a unique deposit which I have examined at Holguin, Cuba, Province of Santiago. Cuba represents a basic magmatic province, and while there is in it much iron, nickel, and manganese, and though there are many showings of copper, all normal to a basic magma, the Holguin mine is the only Cuban gold mine of which I know. It is, indeed, not of importance—more of a prospect—but its geological occurrence is interesting.

The general formation at the mine, and for miles around, is a coarse basic diorite, consisting of hornblende and feldspar, and varying considerably in basicity. This rock has been sheared, intensely so in certain zones and belts, with the development of serpentine. Later than the shearing are aplitic dikes, following the general direction of the schistosity. Some of these are light colored, some dark. One of these dikes is purely feldspathic—of albite—forming an albitite or soda-trachyte, as determined for me by Dr. F. E. Wright. Another, parallel, has numerous small dark phenocrysts, apparently of hornblende. The dark dikes are largely of hornblende—hornblendite with very little feldspar. This indicates the consanguinity of the different rocks. The light and dark dikes are plainly complementary, and derived by differentiation from the diorite magma represented by the main igneous mass.

The albitite dike, which is from 2 to 20 feet wide, has been crushed in certain portions, and the close-set fracture planes have been traversed by mineralizing solutions, which have bleached and softened the rock on either side of the fracture. Pyrite and native gold (probably primary) have been deposited in thin films along the fracture planes, and there is also a little disseminated pyrite in the bleached rock. The ore appears to have practically no gangue; but it is associated with tiny calcite stringers, usually only a fraction of an inch thick, which inclose scattered pyrite like that along the fracture planes.

The ore deposition, therefore, followed the trachytic aplite injection, and was due to scanty solutions carrying gold and a little pyrite, and very little else. Gold-bearing quartz is entirely absent.

This aplitic albitite dike, dense and light colored, carrying gold, and resembling a vein, has, I believe, often been mistaken for a mineral vein by those who have examined it.

The occurrence is of great interest to me, for it shows that the segre-

One striking thing about this triple sequence is the fact that copper, zinc, lead, and silver, the minerals not formed at the higher temperatures, are common to all lines of descent; and that it is the high-temperature elements, those first emanations most closely related to the fabric of the igneous rock whence they have been excluded, which are characteristic and indicative of their special magma-origin. However, of these key metals, nickel, gold, and tin, representing the basic, intermediate, and siliceous lines of descent respectively, the first two at least recur in the later, lower-temperature groups in a minor way. Nickel, for example, occurs not only in its proper zone, on a grand scale, in Sudbury, in the great basic-magma province which lies east of the Rockies, but occurs in a minor way in the great copper deposits of Michigan and the great silver deposits of Cobalt, all of which belong to the same great general basic-magma province; and even in or near the Missouri lead-zinc districts, which probably also belong to the same province.

Gold has the same characteristic, and much more markedly, of reappearing at various horizons or temperature zones. Occurring rarely in the pegmatites, one of its most important horizons and perhaps its main simple horizon of occurrence is in the deep-seated gold-quartz veins; it reappears, however, in the gold-arsenopyrite veins, which occupy a somewhat higher horizon; and, finally, it seems to occur in places as an uppermost ore zone, overlying the main silver zone.

Gold deposits have the habit of occurring in volcanic

---

gation of gold is not entirely foreign to basic magmas; and yet this exception proves the rule, especially as the occurrence is of slight economic importance, even though it was credited, at the time of my examination in 1912, with a gross production of $100,000 or more. My sampling showed that while large masses of the rock might run $3 to $5, the average of the whole dike is less than $1.

The lack of quartz, and the presence only of a little calcite with this ore, is a distinguishing feature of many basic-magma-derived ores, which I have described in the case of copper ores like those at the Bonanza mine, in Alaska, and elsewhere (p. 598).

rocks, partly (among other reasons indicated above) because the temperature is elevated to the range which in the deep zones as well is critical for the precipitation of this metal. This habit is also characteristic of tin, as illustrated by the foregoing notes regarding Bolivia, and by the occurrence of tin in Tertiary rhyolites in Mexico and Texas. It is also characteristic of tungsten. But it is a habit which apparently is not shared by the basic member of the sequences. Neither chromium, platinum, nor nickel, it seems, all characteristic of the deep zones, reappears in the volcanic rocks under any circumstances; although, as above seen, nickel may persist in the zones above its main zone of occurrence. The necessary conditions for the occurrence of these metals are apparently not reached in the basic lavas; therefore, we do not find in these the recurrence and frequent telescoping of two or more—sometimes all—of the deeper vein zones, which is very characteristic of the intermediate gold-bearing vein sequence, and to a minor extent, apparently, of the very siliceous or tin-bearing vein sequence. Basic superficial lavas (basalts) are practically devoid of ore deposits, while the intermediate-siliceous superficial lavas—andesites, trachytes, and rhyolites—are rich in them. The lack of ore deposits in the basic superficial rocks may be due in some way to the relative lack of water and of the other gaseous elements as well as silica in the basic-magma-derived ore magmas, which aqueous-gaseous elements are very much to the front in intermediate-magma-derived ore magmas, and have come to be considered as highly typical and necessary in the siliceous-magma-derived ore magmas. Perhaps, on account of the relative lack of these accompanying gaseous elements, the heavy basic-magma-derived ore magmas lack the buoyancy which would enable them to climb far up from their deep locus of origin, as the ore magmas derived from the more siliceous rock magmas have the power to do.

Silver, like gold, is not wholly static in respect to its normal zone occurrence, especially in the intermediate-

magma vein sequence. While the chief zone of silver is the uppermost of the simple sequence, and occurs overlying the galena zone, yet silver also occurs in the galena zone, and, still deeper, in the pyrite-pyrrhotite zone which underlies the blende zone and overlies the copper zone, and which may be argentiferous to a marked degree, as at Matehuala and Santa Eulalia.[14] Neither is molybdenum wholly static, for while molybdenite certainly has its chief vein zone in the pegmatites and in pegmatitic quartz veins,[15] I have noted it, for example, at Helvetia, Arizona, in quartz-calcite veins later than cupriferous pyrite veins which occur in their normal zone of temperature.

On the other hand, in the normal ore zones, the metals copper, lead, and zinc appear to be static, and to occur, to an important degree, only at one temperature horizon each; and this is apparently true in all three vein sequences, basic, intermediate, and siliceous. In the intermediate and siliceous sequences, these zones (of copper, zinc, and lead) may appear, as above noted, in the superficial lavas, and may be mixed or telescoped with one another, and with still higher and still lower zones.

Of the principal metals mentioned in the table on p. 611 gold is perhaps the most migratory, appearing not only in its own characteristic deep vein zone, but, as noted, higher up, in the auriferous arsenopyrite zone, and again apparently at the very top of the metal sequence, where (in the case of the Mercur ore, for example) it is sometimes closely associated with arsenic and mercury. The agency of arsenic in carrying gold above the zone where it occurs largely alone and native (the gold-quartz zone) into these different upper zones, is to be inferred.

At the same time it is seen how migratory is the habit of arsenic, which is fixed in mineral form at various temperatures and pressures. Doubtless it is most abundant in the chief arsenopyrite zone, which is later than the gold-quartz

[14] See pp. 259 and 317.

[15] See Chapter XII, p. 585.

zone, and in some cases at least (Matehuala, see p. 258) later than the principal copper (simple copper sulphides and native copper) zone. But it also occurs in the main silver zone, where it forms complex compounds with silver, copper, etc., such as tennantite; and finally it also appears at the very top of the vein sequence, as noted in Chapter XI, as probably primary realgar. This recurrent habit of arsenic and its function of carrying more static metals is characteristic of all three vein sequences—basic, intermediate, and siliceous.

Antimony is very similar to arsenic in its habits. Its main zone is uncertain, but it certainly appears at various zones, perhaps chiefly in or near the chief galena-blende zone, as at the Sirena mine, at Zimapan, Hidalgo, Mexico, where antimony occurs as jamesonite with galena-blende ores, as I have observed, and as afterward was more carefully studied by Lindgren and Whitehead.[16] Again it occurs in the principal silver or tetrahedrite zone, where it plays the same rôle as arsenic in the formation of copper and silver-bearing complex sulpho-compounds, and has been, apparently, like arsenic, an important carrier of silver. Finally, like arsenic, it occurs in very superficial deposits, as stibnite, and in not inconsiderable quantity.[17]

Selenium and tellurium are rare metals which also do not occupy a fixed zone, but belong in the class of highly mobile elements, like arsenic and antimony. They occur to a limited extent in the deeper vein zones, but are most characteristic of superficial deposits in lavas. They are great carriers of gold and silver, and occur principally in combination with them.

By way of summary, it may be said that while the chief vein zones shown in the table on p. 611 are very characteristic and uniform, yet some of the metals, by effecting combinations with the volatile elements, including mobile metals important in the constitution of the ore magma,

[16] *Econ. Geol.,* Vol. IX, 1914, pp. 435-462.

[17] See p. 544.

secure transportation to one or more upper zones, and in various combinations and with various degrees of efficiency. While copper, for example, is only transported from its main zone (where it occurs in combination with sulphur only, and in native form) to the principal silver zone by the aid of arsenic and antimony, and zinc is practically not transported at all from its characteristic sulphide zone, gold is very efficiently so transported, by the aid, apparently, of antimony and arsenic, and of tellurium and selenium. In general, certain metals of the vein sequences (given on p. 611) (from which the mobile metals are excluded as having no sufficiently regular zone) occur in the sulphide form or native in their principal zone of deposition; and where they occur in the upper zones, usually in a less relative quantity, they are found combined with arsenic and antimony, or selenium and tellurium.

It will be noted that I have laid little stress on fluorine, chlorine, and boron in the above, as compared with the mobile metals. I do this because of the evidence that these gases, like water gas, are present in all stages of the ore magma and in all the three divisions of vein sequence; hence they form a more or less uniform background to all the stages of the vein sequences, and while an important factor in the general composition and character of the ore magma, seemingly do not determine the migration of metals up past their main sulphide precipitation zone, as do the mobile metals. Certainly, however, these gaseous elements —like fluorine, chlorine, boron, and water—are more concentrated in the intermediate rock magmas than in the basic, and more in the siliceous than in the intermediate; and the same characteristics clearly apply to the ore magma derived from each of these three divisions. Therefore, the tin deposits and the tin sequence show, most abundantly of all, the effects of these vapors, in their association with the minerals containing them or crystallized through their agency, and in the alteration of the wall rocks due to them; while the intermediate ore-magma vein sequence shows

these effects also, to a noticeable but less degree, particularly in the sericitization of the feldspathic wall rocks, which may be observed throughout the whole metal sequence, from molybdenum and tungsten to the uppermost silver and gold zones.[18] In all these zones the sericitization is accompanied by the deposition of silica and of carbonates, showing the presence also of carbon dioxide gas and of excess silica in the ore magma at all stages. Sericitization is due to the influence of fluorine. The ultra-siliceous or tin-sequence ore magma has an excess not only of fluorine, but also of boron, as shown by the characteristic alteration and by the gangue mineral, tourmaline.

In the wall rocks of the ore deposits of the basic-magma-derived vein sequence alteration is much less marked, and sometimes there is little or none. At Sudbury, alteration of the wall rocks of the nickel ores is practically wanting,[19] whether the wall rock be norite or granite; and at Cobalt, also, the silver-bearing veins show practically no alteration of the walls (mainly diabase). At Kennecott, in Alaska, the copper deposits in limestone have produced no alteration of the walls, not even silicification, although the greenstone is altered and shows albite, chlorite, epidote, calcite, and zeolites. None of these products indicate the action of fluorine, chlorine, or boron; and excess silica seems to have been absent, although carbon dioxide was present. Therefore, a marked difference of the basic-derived ore magma

[18] For the alteration of the wall rock of molybdenite, tin, and tungsten ores to sericite, see, for example, E. C ANDREWS: New South Wales Geol. Surv., Mineral Resources No. 11, "Molybdenum," p. 14; for the deep gold-quartz veins, N. R. JUNNER: "Gold Occurrences of Victoria," *Econ. Geol.*, Vol. XVI, No. 2, p. 87; for the principal copper zone, Butte, W H. WEED: *Professional Paper* 74, U. S. Geol. Surv., 1912, p. 83; for the auriferous pyrite and blende-galena zones, J. E. SPURR: *Professional Paper* 63, U. S. Geol. Surv., 1908, pp. 143-150; for the principal silver zone, the Divide (Nevada) district, A. KNOPF: Bulletin 715-K, U. S. Geol. Surv., 1921, p. 159; and for the gold-silver group of Tertiary volcanic ores in general, Tonopah, Nevada.

[19] Report, Royal Ontario Nickel Commission, Toronto, 1917, p. 130. See, however, footnote 45, Chapter XII, p. 597.

is seen, in its relative poverty in the gaseous elements save carbonic acid and water, and its poverty in silica; and in some cases, as at Sudbury and Cobalt, in its poverty also in water and carbonic acid, leaving a comparatively dry ore magma with not very much in the way of excess material after the magma had crystallized in the veins.

Going over the ground once again from a slightly different standpoint, the Sudbury ores show no gangue, save a little quartz and calcite of slightly later origin; the Cobalt veins have a gangue of calcite and dolomite; in the copper mines of Kennecott, as above stated, there has been no silicification of the limestone, although the diabase shows some calcite. In the Michigan copper mines, which are in conglomerates and basic lavas, calcite is often a contemporaneous gangue for the native copper; and I have noted[20] that the solutions which accompanied the ore deposition must have replaced silica with ease, since they have dissolved the sandy matrix of the conglomerates and filled the spaces thus provided, with calcite and other minerals: "Solutions capable of dissolving silica and later precipitating calcite, or of replacing silica and other constituents by calcite, are indicated.[21] The small amount of alteration of the rocks of the lode is, however, remarkable. The rock of the lode is apparently little more altered than are the wall rocks." Veinlets carrying sulphides and arsenides have a sparse quartz-calcite gangue.

It appears then that the sulphidic ore magma derived from the basic-magma end of the series is, aside from its metallic sulphide and arsenide solutions, calcic rather than siliceous, but that the earthy constituents, including calcite, are relatively scanty; and that the same is true of water and other gaseous constituents, such as fluorine or boron. All these gaseous constituents are sometimes present,

[20] *Eng. and Min. Jour.*, Vol. 110, No. 8, p. 356.

[21] At Matehuala it was found that at a certain stage calcite replaced quartz and other siliceous minerals with ease. See SPURR, GARREY and FENNER: *Econ. Geol.*, Vol. VII, No. 5, p. 465.

nevertheless, as shown by minerals like apophyllite and datolite, characteristic of many copper deposits in the basic rocks. Silicification and sericitization is not characteristic of the basic-vein sequence. Therefore, in the Mississippi Valley, the fact that besides the lead and zinc ores of this province, there is locally a remarkable development of veins of fluorite and of barite, but no quartz veins, demonstrates to me again that this is probably all part of the great underlying basic-magma province.

The basic-magma-derived ore-solution magma, therefore, is calcic, non-siliceous, and with scanty excess material, whether earthy constituents, water, or gaseous elements (including sulphur); while the siliceous-magma-derived ore-solution magmas are siliceous, aqueous, gaseous, and non-calcic; and the corresponding effects on different wall rocks of these opposed types of solutions are characteristic and typical.

All this shows that ore deposition in general is almost independent of water and the gaseous elements, like fluorine, boron, and chlorine, commonly called the "mineralizers" and often supposed to be the great carriers of metals in solution. The basic-magma-derived ore solutions are as abundant and precipitate ore as freely as the siliceous-magma-derived ore solutions, and probably in the same range of temperature; and thereby the same conclusion is again reached as was arrived at above in considering the work of arsenic and other mobile metals as carriers for gold and other metals—namely, that abundance of water and the gaseous elements is not an essential; and that these elements, though they certainly play an important part in keeping any magma solution fluid, whether it be rock magma or ore magma, need be present in only very small amount for that purpose; and, that purpose being accomplished, any further amounts are in general superfluous. It is hardly significant or constructive, therefore, to classify certain gold or certain copper veins separately because they are associated with tourmaline, either in the vein or in the

wall rock; for this mineral is to be regarded as a more or less inconsequential associate, and not as a determining or qualifying factor.

It goes without saying that if the basic ore magma is calcic, non-siliceous, highly concentrated as to metallic sulphides and arsenides, poor in water and the gaseous elements; and the siliceous ore magma is siliceous, non-calcic, rich in water and the gaseous elements, with the metallic sulphides, arsenides, etc., correspondingly diluted, the intermediate ore magmas will show various combinations of these opposed characteristics, depending upon whether they approach the one extreme or the other.

One thing remains to be discussed—the contrast between the hydrous lime silicates so often characteristic of basic-magma copper deposits, and the non-hydrous lime silicates so often characteristic of the siliceous-intermediate magma copper deposits. In the latter case, we know from many studies that where siliceous ore-solutions meet limestone and directly react with it, or absorb it and pass on as a partly calcic solution,[22] the lime-silica combination is formed which produces these striking and characteristic silicates, like garnet and hornblende. Since the basic ore-solutions are calcic, and since typically, as at Kennecott, they form no zeolites or other lime silicates in limestone, but do form them in greenstone, evidently, then, the occurrence in the latter is due to the combination of the lime in the solution with the silica and alumina of the igneous rock. In other words, the reaction is in a sense reversed: lime silicates may result from the action of siliceous solutions on calcic rocks or minerals, or, contrariwise, by the action of calcic solutions on siliceous rocks and minerals; or, finally, by the action of silicic-calcic solutions on any rock.

But why should the lime silicates formed in basic rocks by calcic magmas be so strikingly of the hydrous variety? I have felt that the rare hydrous silicates observed at Mate-

[22] Note my conclusions at Velardeña, *Econ. Geol.,* Vol. III, No. 8, p. 724.

huala,[23] although the microscopic observations were scanty, throw more comparative light on the subject than anything else that I have known. The Matehuala ore magma was intermediate-magma-derived, its mother rock being quartz monzonite; and the great mass of lime silicates are of the non-hydrous variety typical of the intermediate and siliceous vein-sequences at the copper stage.

Several things regarding the rare hydrous silicates at Matehuala are important. They are plainly the work of magmatic waters, since they are part of the orderly sequence of minerals which is found in that district. They represent a definite stage in the metamorphism or metasomatism, and not the latest stage. They consist of zoisite and prehnite (hydrous lime-alumina silicates), epidote (hydrous lime-alumina-iron silicate), and apophyllite (hydrous lime-potash silicate); all of which are characteristic of the alteration of basic rocks attending copper deposition from basic-magma-derived solutions, where, however, they are abundantly present. At Matehuala they are not minerals produced by percolating surface waters (as they have been interpreted to be in the Michigan copper mines and elsewhere), and they are not low-temperature minerals, as is shown by the occurrence of epidote of the same age as orthoclase in one case, and as cupriferous pyrite. All the hydrous silicates here seem to be of very much the same age, which is the age of the metallic sulphide deposition; and as these are so-called "contact-metamorphic" deposits of copper, they have commonly been supposed to have formed at a very high temperature. I have tried to explain in many places in these pages that there has been much confusion over this idea of "contact-metamorphic" ore deposition, and that the copper deposits thus associated with lime silicates near or at contacts of intrusive igneous rocks into limestone are probably deposited at much the same general range of temperature as copper veins in general: in intermediate to siliceous igneous rocks, as at Butte; in siliceous rocks, as

[23] *Econ. Geol.*, Vol. VII, No. 5, Aug., 1912, pp. 475-6.

in Cornwall; or in basic rocks, as at Kennecott and in Michigan.

At Matehuala, of two sets of specimens, one showing the alteration of limestone to lime silicates (garnet, pyroxene, wollastonite, vesuvianite) calcite, and quartz, and the other showing the alteration of monzonite to lime silicates (garnet, pyroxene, wollastonite, vesuvianite) calcite, and quartz, the hydrous silicates (prehnite, zoisite, epidote) were noted only in the metamorphosed igneous rock, and not in the metamorphosed limestone, recalling the similar distinction maintained at Kennecott (p. 597). In other words, and as far as these two rock-specimen series which I am discussing go, if we eliminate from each series the (by far the most abundant) metamorphic minerals which are common to both (garnet, pyroxene, wollastonite, vesuvianite, calcite, and quartz), we should have no alteration of the limestone, but a development of prehnite, zoisite, and epidote in the monzonite alone.

These minerals could not have been formed by the action of siliceous or siliceous-aluminous solutions. While the abundant lime silicates common to both limestone and monzonite are the result of replacement (or metasomatism), the rare hydrous silicates, observed chiefly in the monzonite, are mainly the product of alteration—prehnite and epidote from the soda-lime feldspars, chlorite from hornblende, etc.

Comparing these observations with those on the development of hydrous silicates associated with copper deposits in basic rocks, we recall that the aqueous solutions which have accompanied or followed the copper deposition in basic rocks are calcic rather than siliceous; that typically, therefore, they do not attack limestone, but alter the silicates of igneous rocks, largely to hydrous compounds.

Most of these hydrous silicates due to alteration are indeed silicates rich in lime. While at Matehuala, the silicates replace feldspar, the most basic of the feldspars here (labradorite) contains 12 to 15 per cent lime, and makes up the centers of phenocrysts, the outsides of which are

of andesine (8 to 10 per cent lime). These feldspars are replaced by prehnite (27 per cent lime), epidote (20 to 24 per cent) and zoisite (21 to 24 per cent). The soda which is present in these plagioclase feldspars is not represented in the replacement minerals. The process of alteration appears to be a deposition of lime, and a taking up of silica and soda (andesine has 55 to 58 per cent SiO_2 and even labradorite 49 to 53 per cent; while prehnite has only 44 per cent, zoisite 39 to 41 per cent, and epidote 33 to 39 per cent); and must here at Matehuala (as elsewhere) be ascribed to calcic solutions, operating at a higher temperature than that which effected the observed copious later replacement of silicates and quartz by calcite.[24] This last-named calcite stage overlapped at the end of the period of sulphide deposition and succeeded that period; indicating again that the hydrous calcic-silicate period more nearly represented the ore period. The formation of these minerals at Matehuala must have been due to solutions which were rendered predominantly calcic by a previous precipitation of the silica. They represent the lime stage of solutions which at Matehuala and Velardeña had the sequence of changes as follows:

A. Alumina-silica-lime
B. Silica-lime
C. Silica-lime-metals
D. Lime

In this sequence (derived from an intermediate magma) the hydrous lime-silicates occupy the first stage of D. But at Kennecott the alumina-silica is wanting in all three stages, and we have a predominantly calcic ore-solution (derived from a basic magma) at all stages and temperatures.

[24] "Many hydrated silicates have been obtained under conditions which point to their formation from solutions at temperatures above 400°, and therefore presumably from fluid (not liquid) solutions." (MOREY and NIGGLI: *Am. Jour. Ch. Soc.*, Vol. XXXV, No 9, p. 1102.)

CHAPTER XIV

Calcic Metamorphosing Solutions on Intermediate Rock Contacts

This chapter describes an example (the Bonanza mine, in Zacatecas, Mexico) of lead-zinc-silver ore deposits near a monzonite-limestone contact, where lime silicates have been formed in the monzonite at the contact, but not in the limestone, indicating highly heated calcic solutions. At the near-by Aranzazu mine, along the same type and age of contact, copper-zinc ores have been formed, and lime silicates have developed at the expense of the limestone, indicating highly heated siliceous solutions. The White Knob copper mine, in Idaho, described by Umpleby, is probably similar, as regards the type of solution which formed lime silicates, to the Bonanza mine. Superheated calcic solutions, forming lime silicates at the expense of igneous rocks, are also indicated at certain stages, for the Helvetia mines in Arizona, for the Copper Queen mine at Velardeña in Mexico, and for the Descubridora mine, also in Mexico.

THE CONCLUSIONS of the last chapter were that while the ore-magma solutions derived from siliceous magmas were highly siliceous, with but little lime, the corresponding solutions derived from basic magmas were calcic, with little silica; that this difference, however, did not seem to affect the potency of metallic ore formation of either, since from both types of solutions, after the abundant separation of the metals peculiar and idiosyncratic to each, the same series of metals—copper, zinc, lead, and silver—were abundantly thrown down. That the earthy gangues, whether quartz or calcite, are not an essential part of the sulphide magmas, is thus demonstrated afresh; and incidentally again, in view of the evidence of a very widely varying amount of water and other gases like fluorine, boron, etc., while metallic sulphide deposition remains constantly heavy, there is demonstrated the fact that water and these gases, the abundance of which has

been long supposed to be the *sine qua non* of ore deposition, are really necessary, if at all, only in very small relative amounts.

Since basic-magma-derived ore solutions are calcic, and siliceous-magma-derived ore solutions are siliceous, it follows, as was pointed out, that ore solutions derived from intermediate magmas would be siliceous-calcic, and so would at the requisite temperatures form lime silicates in both limestone and in siliceous igneous rocks; while the purely siliceous ore solutions would only form lime silicates from limestones, and the purely calcic ore solutions would (and do) form lime silicates only in the igneous rocks where silica is available.

I have further pointed out that a siliceous-calcic residual solution, whether an ore solution or non-metalliferous, working through abundant limestone, would and frequently did have its siliceous portions removed, by reaction with limestone, to form lime silicates, leaving the residual solutions wholly calcic, though derived from intermediate magmas, or even from siliceous magmas (in the latter case the surviving calcic portion not being original, as it would be in part in the case of the intermediate magmas, but almost entirely derived from the limestone, in the place of deposited silica). At Matehuala, the finally calcic nature of the residual magma solutions was shown—the result, partly, of this interchange; and at Matehuala the solutions at this calcic stage were just at and directly below the critical temperature for lime-silicate formation, and resulted mainly in the formation of calcite, instead of lime silicates, which calcite replaced earlier quartz and silicates. The rock magma at Matehuala is an intermediate one. We have there a long recorded sequence of lime-silicate and post-lime-silicate contact metasomatism and metamorphism, of which only the last stage records a calcic solution, while the main period records a siliceous-calcic solution. I shall now in a short chapter describe a striking occurrence, not so very far from Matehuala, where the only recorded lime-

silicate formation is the result of calcic residual solutions, not associated with basic magmas, but with intermediate magmas.

In the State of Zacatecas, in Mexico, in the vicinity of the Bonanza group of mines of the American Smelting and Refining Company, the geology offers some vitally interesting features and some clear and absolutely new lessons. The mines are reached by rail from the city of Saltillo. They are in an irregular group of mountains called the Sierra de Mazapil, and form part of a considerable group of ore deposits of which more important ones have been worked by the Mazapil Mining Company, with a smelter at Concepcion del Oro.

In the Sierra de Mazapil, we find the same sedimentary rocks as we do all over this portion of Mexico—the thick upper shale series and the thick underlying limestone series, both probably Cretaceous[1]; these have been intruded by masses or stocks of monzonite. Ore deposits (mainly of argentiferous galena) occur at Bonanza, in limestone near an intrusive monzonite contact.

The ores do not occur in the contact, or rarely so. They follow a strong fissure zone which runs parallel to the contact, and about 70 meters (230 ft.) from it. (Fig. 97.) Another strong parallel line of fissures, along which another string or chain of ore deposits (mainly pipes or chimneys of argentiferous lead ore, containing some gold) is localized, is about the same distance again (70 meters) still further away from the contact.

The first zone, while it follows the trend of the intrusive contact faithfully, and bends with it, is straighter than the contact (of course, a fissure ought to be straighter than an intrusive contact), so that its distance from the contact varies locally from 70 meters or so down to 30 or less, and

[1] The sedimentary rocks in this region form a series from the Jurassic to the upper Cretaceous, according to Dr. Carlos Burckhardt, who has carefully studied and divided the different horizons (Congrès Géologique Internationale, 1906. "Géologie de la Sierra de Concepcion del Oro," p. 2, *et seq.*).

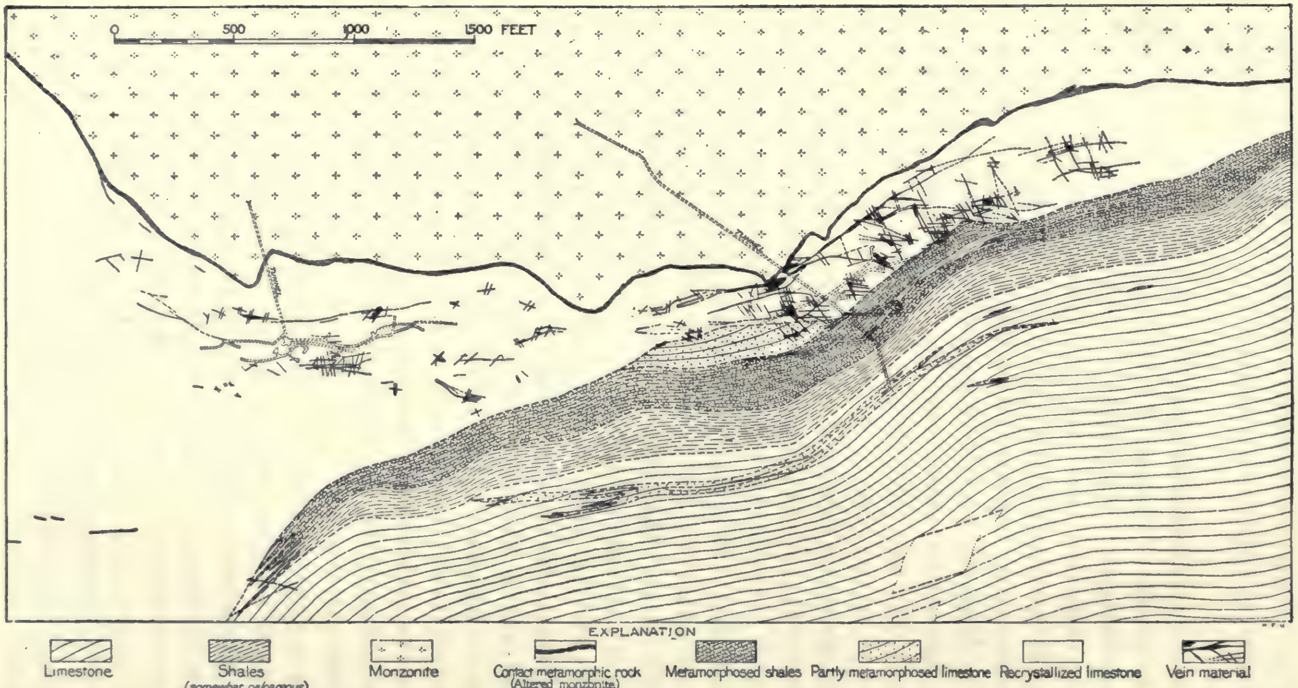


FIG. 97.—Bonanza mine, Zacatecas, Mexico. Map of surface geology near mine. Illustrates lead-silver orebodies formed along fissures in limestone, following an intrusive contact of monzonite; shows, also, and especially, the alteration of monzonite to lime silicates at the exact contact, by superheated calcic solutions, earlier than the ore deposition. Careful instrumental survey. The long side of the illustration runs due north and south, the north being to the left.

at one point where the usually not very irregular contact sends out a cape or point, the fissure zone actually skirts the contact; but as this parallelism between main ore fissure zone and contact obtains over a longitudinal stretch of at least 1,200 meters (nearly 4,000 ft.), which is the stretch that was carefully mapped, you will agree that the fixed relation between ore location and contact is remarkably faithful.

Still closer is the parallelism of the first ore zone or fissure and the second, which I have mentioned as some

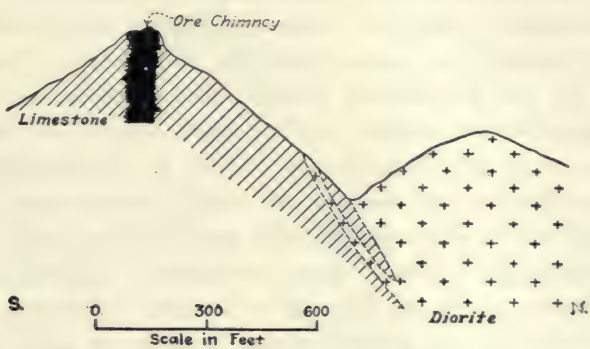


FIG. 98.—Beatrice ore chimney (oxidized lead-zinc ore) near Bonanza, Zacatecas, Mexico. Shows localization of ore chimney in limestone near contact of intrusive diorite. The delicate effects of differential erosion in this arid country are exhibited. The ore chimney is siliceous, and has "held up" the hilltop, while the surrounding rocks have been worn away faster.

70 meters (50 to 70) beyond the first, away from the monzonite contact. This second ore zone is partly manifested by an actual ore-accompanied fissure continuous for long stretches (as much as 400 meters at a stretch) parallel to the contact, and so really constituting a strong continuous fissure vein in limestone (although the oreshoots are mainly due to the junction and intersection of cross-fissures); and more strongly manifested as a chain of ores due to a network of intersecting fissures, belonging to both the parallel and the transverse systems. For the system of fractures transverse to the contact (predominantly at right angles

and to a lesser degree oblique) are as characteristic of this near-contact zone as are the parallel fractures, and are more numerous, though not so strong. The whole belt of ore deposition, in the Bonanza group of which I am speaking, and covering only the carefully mapped 1,200 meters or so mentioned of this very extensive contact (which I have otherwise but sketchily explored), is confined to a width of 100 to 150 meters from the contact. Figure 98, of the Beatrice ore chimney, considerably beyond the stretch mapped, shows the same general relations.

On the walls of some of these fissures in limestone, which are frequently clean-cut, movement striæ were observed, dipping usually not more than 15 to 20° from the horizontal, on the movement plane. Nevertheless, no actual faulting, recorded in the relative displacement of rocks on the two walls of a fissure, was noted; so that the fissures plainly represent the fissures of slight displacement which are everywhere characteristically occupied by ores. They are, accordingly, fissure veins, genetically speaking; but most fissure veins in limestone behave differently from fissure veins in less soluble rocks, because at junctions or intersections of fissures in limestone there is more extensive ore deposition, due to replacement; and there is correspondingly less on intervening stretches of the fissures, where there is no intersection, so that the workable ore-bodies occur in irregular pipes, as they do here at Bonanza. Nevertheless, the continuous though commercially unprofitable fissure veins which tie these chimneys together are not only theoretical but strongly a tangible fact in this district, as may be seen from the map of the ore in the Providencia tunnel (Fig. 99) as well as the surface map (Fig. 97); and especially in the surface plan of the Providencia mine section (Fig. 100), where a ground model of branching fissure veins is clearly indicated.

These fissures, therefore, conform to the law indicated at Matehuala[2] (where, however, the fissures are mainly

[2] P. 722, Fig. 124.

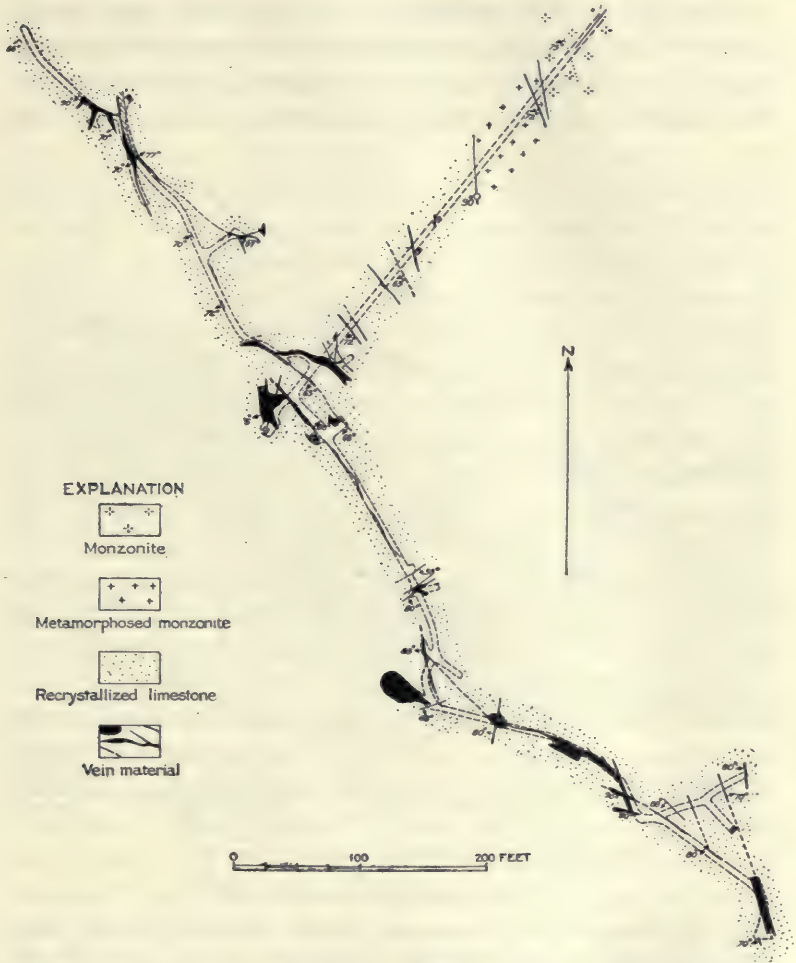


FIG. 99.—Bonanza mine, Zacatecas, Mexico. Inner portion of (main) Providencia tunnel. Shows monzonite-limestone contact, with the monzonite altered along the contact to lime silicates, but the limestone unaffected. Shows, also, ore in limestone, controlled by fissures, as is usually the case in other rocks; but here more irregularly, leading to pipes and chimneys at intersections, more than in the case of less soluble rocks. By G. H. Garrey.

within the igneous intrusion), in that they are mainly divisible into two sets, parallel and transverse to the elongation of the intrusion; and the localization of the belt near the contact, the very slight fault-fissure nature, and the

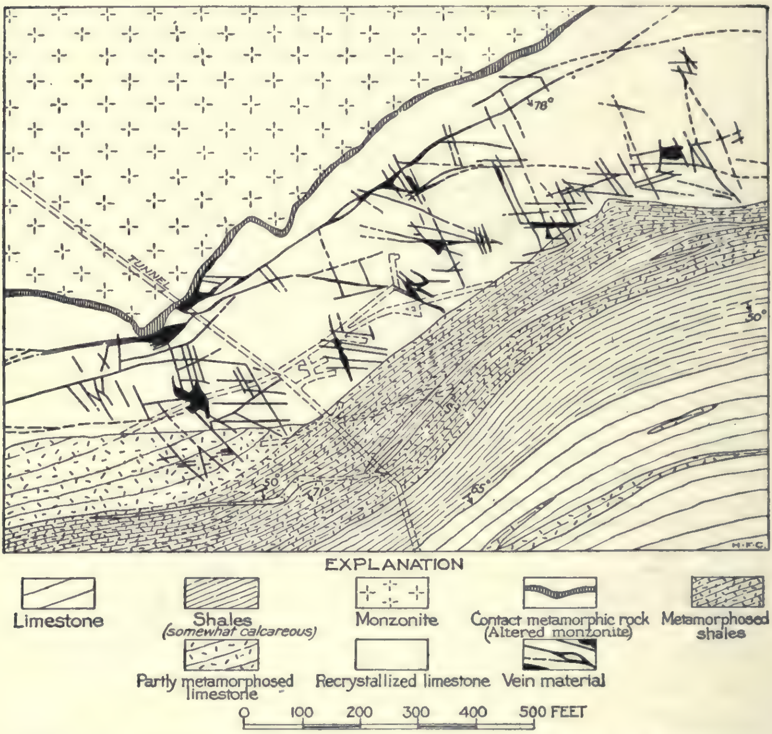


FIG. 100.—Bonanza mine, Zacatecas, Mexico. Detail of Fig. 97, larger scale. Showing chief mineralized area; the dependency of ore in limestone on fissures and their intersections; and the metamorphism of siliceous rocks (monzonite and shale) by superheated calcic solutions, while the limestone has merely been recrystallized.

movement striæ approaching the horizontal, all show that they belong within that group of numerous slight fissures which are due to adjustments in position of the intruded magma, as it consolidates and sets up contractile strains. I refer to the magma in depth, not that zone or horizontal slice now exposed by erosion, for although the veins at

Bonanza do not occur in the monzonite, they are later than the monzonite, as I will presently show.

The ores are not associated, I wish to say in advance, with lime silicates in any way. They replace a limestone which has been recrystallized—marmorized—such as we often see near an igneous intrusion. And in regard to the extent of this marmorization or marbleization, I must describe another geological factor, which I think perhaps of sufficient interest to cite, calling attention at the same time to the geologic plan (Fig. 97). In the limestones there is a belt of shales (limy) about a hundred meters thick, and as the sedimentary beds were turned up almost vertically by the great igneous column, the shale bed naturally tipped up so that its outcrop runs parallel with the igneous contact for a considerable distance; in this stretch it lies about 100 to 150 meters from this contact, the intervening rock being limestone; and it is in this intervening limestone belt that the general ore zone lies, and it is also this intervening belt where the limestone has been marbleized. To the north, the outcrop of the shale bed and the monzonite contact diverge, and while the ore belt still remains faithful to the monzonite contact, the belt of marbleized limestone opens out, following the shale divergence, and attains a great width, certainly 1,000 meters and I do not know how much more, for I have not mapped it further. But on the side of the shale belt away from the monzonite, where another belt of limestone lies, this limestone is not marbleized. Thus it is very clear that solutions, rising in the general vicinity of the igneous contact, were confined by the shale belt, which dips very steeply away from the contact, so that they did not affect the limestone on the far side. The circumstance of the shale being such a decisive factor in limiting the field of recrystallization or marbleization of the limestone, shows that the marbleization was indeed accomplished by solutions, and not by the heat of the intrusion.

On the contact of the limestone and the monzonite, you

will see mapped a very continuous and very regular and narrow belt of garnet rock. This regularity and continuity is a quite unusual thing in my experience; and on superficial observation I said, "Here, apparently, is what I have never seen before—the formation of lime silicates by the emanations of the cooling magma which is now represented by this outcropping monzonite—for the regular nature and width of the belt, and its occurrence at the exact contact, indicates clearly a relation with that part of the rock magma now exposed." How easy it is to fall into error! Careful examination everywhere showed that this lime-silicate belt (of garnet and other lime silicates) which is 50 to 100 feet wide, has formed entirely by the alteration of the monzonite, at the contact, and that the limestone comes up to the exact original igneous contact with no alteration to lime silicates whatever! Here is an unexpected and extraordinary occurrence, but an indubitable fact. The bulk of the work here was done by Mr. George H. Garrey, working under my direction, and he was assisted principally by Mr. J. A. Farrell. The mapping was done largely by Mr. Farrell, checked by Mr. Garrey and myself. Regarding the "contact-metamorphic" border, I will condense from Mr. Garrey's unpublished field notes. He is describing the Providencia adit tunnel, which, starting in the monzonite, crosses the contact into the limestone and the ore zone (Fig. 99):

"The main tunnel in the outer part is in comparatively fresh monzonite; for the most part the monzonite is rich in feldspar. Biotite is conspicuous, and quartz phenocrysts are sparsely present. As the contact with the limestone was approached, the fresh monzonite became bleached to a yellowish color, and in spots and occasional isolated patches greasy-lustered silicates began to appear, the gradual transition from the comparatively dark fresh monzonite to a gray dense structureless rock being apparent; and then the increasing admixture of reddish brown garnet and other silicates. For a width of about sixty feet on the actual

contact, the metamorphosed monzonite consisted chiefly of a mixture of greasy-lustered reddish-brown garnet and other silicates and the grayish-silicate rock. However, scattered all through this contact zone are recognizable patches both of dark-colored fresher monzonite and the light-colored bleached monzonite. The contact between the gray or white crystalline limestone and the metamorphosed monzonite zone was marked only by two or three inches of a yellowish or pinkish fine-grained pulverulent material, due partly to the alteration of the limestone and partly to slight oscillatory movement along the contact, but does not represent a fault plane."

Near another mine in this district outside of the area shown on the map (Fig. 97), where the same relations obtain, Mr. Garrey notes, "The remarkable point noted was the intense metamorphism of the igneous rock; and yet this metamorphosed monzonite, with patches of fresh monzonite inclosed, occurred within six inches of practically unaltered gray limestone. That is, there was no metamorphosed limestone in evidence."

Here, certainly, is contact metamorphism, or metasomatism, but one would say offhand, from the facts, that the situation was reversed from that usually expected, and that it was the limestone which had metamorphosed the monzonite. Indeed, in a way the phenomena admit of no other explanation, if for limestone we substitute the word "lime." The solutions which rose up between the steep monzonite contact as one wall and the steep (about 65° dipping) shale as the other wall, and which strikingly recrystallized the limestone in the belt between, did not carry silica or any other substance which could have replaced lime: thus the only result was the recrystallization of the lime. The solutions were, therefore, aqueous, although doubtless at high pressures and temperature. They carried lime, of course, if only for the reason that in their passage through the limestone and in their work of recrystallizing lime they became calcareous. At the mon-

zonite contact, they acted powerfully on the silicates of the igneous rock, forming lime silicates, such as garnet, for a regular distance of 50 to 100 feet; beyond which, in the monzonite, the alteration to lime silicates fades rapidly away. Now, the fact that these aqueous solutions (calcareous, of course, as well) transformed the normal rock silicates to lime silicates like garnet exposes the fact that the solutions were under high temperature-pressure—that, in fact, they were well above the critical temperature of water (365° C.), for these lime silicates do not form below around 500° C. (see pp. 262, 263).

Did these aqueous gases affect the shale wall of the limestone belt, on the opposite side (from the monzonite contact) of the elongated narrow channel formed by this belt? They did; they altered it for a greater thickness than they did the monzonite. The shales were plainly more pervious than the monzonite or were more strongly affected because they were the hanging wall of this limestone belt which was traversed by ascending water gases, while the monzonite was the footwall. The total width of the outcropping shale belt is about 100 meters, and about one-half—that half adjoining the marbleized limestone and facing the monzonite—has been altered to lime silicates. The other half—that facing unaltered blue limestone on the other side of the shales, and facing away from the monzonite—has not been metamorphosed.

This clear instance adds another link to the chain of evidence as to the significance of lime silicates in connection with igneous intrusions into limestones. I have shown at Velardeña and at Matehuala that the formation of lime silicates was due to solutions containing both lime and silica, and so intense and hot that they altered the igneous rock (monzonite or diorite) and replaced it to form lime silicates as freely as they did the limestone, if not more so. Such solutions, since they replaced the limestone, contained silica; since they transformed also the monzonite and diorite to lime silicates, they contained lime. They con-

tained more silica than did some of the igneous rocks, as, for example, is shown at Velardeña, where their metasomatic effect has been markedly greater on the basic phases (diorite-diabase) of the intrusion than on the more siliceous (granitic) phases of the same general intrusive magma. At Helvetia, where the intrusive rock is granite, and where in the general vicinity of the granite contact there has been an extensive development of lime silicates, the granite shows practically no alteration to lime silicates (p. 311). In this last case, therefore, the metamorphosing solutions were siliceous, or siliceous-aluminous; at Matehuala and Velardeña, they were siliceous-calcareous or siliceous-aluminous-calcareous. Now, at Bonanza they are shown to have been simply calcareous.

Hence we may arrive at the law that the formation of lime silicates in connection with igneous intrusions is due to aqueous magmatic residues, not only above the critical temperature of water (365°) and so in that condition where the distinction between liquid and gas vanishes, but also above the critical lime-silicate formation stage, or above about 500°. Further, that these aqueous residues may contain in solution a great range of substances; for example, they may be calcareous or they may be siliceous. In the one case they will form lime silicates by reaction with siliceous rocks; in the second case by reaction with calcareous rocks; and so on. Further, that similar solutions, below the temperature of lime-silicate formation, form extensive silicification (if they are siliceous), especially of limestone near igneous contacts. In the complex Helvetia district,[3] where after the initial intrusion of granite into limestone there have been a succession of finer-grained, siliceous intrusions, we mapped not only the igneous intrusions (all evidently successive manifestations of the underlying granite magma) but the different and areally distinct types of metamorphic (or metasomatic) rock. Four were mapped. Three of them involved silicification of the limestone. Their relative age

[3] See p. 310.

was determined to be as follows: 1, Pale-green aluminous silicates and wollastonite. This is areally very widespread and abundant. It has no relation to ore deposition, in which lack of relation it corresponds to every other similar occurrence in other mining districts which I have studied. 2, Dark-colored lime silicates, iron bearing. This is very limited in amount, and restricted, and is closely associated with the copper and other ores of the district. 3, Jasperoid, or metasomatic rock consisting of fine-grained quartz. This is widespread, but not nearly so much so as No. 1, but far, far more than No. 2. While it has formed chiefly (in definite areas) by replacement of the limestone, it has also formed by replacement of some of the igneous intrusives. No. 3 has formed evidently below the lime-silicate temperature, or below around 500° C.; Nos. 1 and 2 above it. No. 2, however, passes into later quartz, calcite, and fluorite, all associated with copper and other metallic sulphides, showing that it was formed just above the lime-silicate temperature, while No. 1 has no such relations, and indicates a relatively high temperature of formation.

The fourth type of alteration near the igneous intrusions was limestone which had been recrystallized and changed from its normal blue color to a light-gray or nearly white color. This occupied definite and restricted areas, and corresponds to the recrystallized and marbleized limestone I am describing at Bonanza. I now perceive that this last type at Helvetia must have been due to hot calcareous solutions.

Once we have grasped the truth that the lime-silicate rocks are due to a great and uncharted range of solutions, the only requisite being the conjunction of lime and silica and a temperature above (about) 500° C., we shall begin to study the differing nature of the solutions in each case, and will find them much varied in nature and origin. Here at Helvetia we have. 1, Abundant siliceous and aluminous solutions; 2, the limited and highly specialized ore magma, containing sulphide solutions, which, by virtue of contain-

ing silica, also formed lime silicates by combination with the limestone; 3, abundant siliceous solutions; and 4, hot calcareous solutions, more limited in quantity and more localized than No. 3, but much less so than No. 2. I have no data on the relative age of No. 4 to the other metasomatic rock-types.

Reverting to Bonanza, and its orebodies, these have no particular relation to the marbleization and the accompanying lime silication. The ores are subsequent; they occur along slight fault fissures which have cut the recrystallized limestone. While they do not occur in any commercial sense at the exact contact of the monzonite, veinlets of clean sulphides, corresponding with the primary type of ore of the orebodies in the limestone near the contact, are found cutting the narrow lime-silicate reaction zone described at the contact. In the ores of the Bonanza, zinc is not present to any considerable degree. The ores are lead ores, highly oxidized; the chief gangue mineral is silica (chert or jasperoid), which is not abundant, and locally considerable fluorite. In La Cueva mine, near the Providencia workings, however, which are not far from the Bonanza, zinc is more conspicuous than lead.

A number of miles from this group lies the Aranzazu mine of the Mazapil Copper Company, which is on a contact of monzonite with limestone, like the contact at Bonanza. I visited the mine briefly. Here strong transverse fissures cut the contact, and the ore occurs along these. Two of them form important fissure veins, with regular walls, running several hundred feet into the monzonite from the contact. Also, some of the best producing orebodies are in limestone up to 200 meters (about 650 feet) away from the contact, but they are along transverse fissures which lead up to the contact. The method of development in this mine is to drive in general along the contact till a transverse fissure is struck, and then to drift both ways on it. The filling of the veins, where they lie in monzonite, is quartz and chalcopyrite and some wollastonite. Following the contact

is a zone of dark-green iron-rich lime silicates—garnet, pyroxene, etc.—like that associated with the copper ore at Matehuala and at the Copper Queen mine, in Velardeña, and elsewhere—and evidently, judging from all these cases, representing the ore-magma period. The main Aranzazu orebody is at the contact, where large chimneys of ore occur. Closely associated with the ore are dark-green silicates (compare Tepezala, p. 279). Besides copper, the ores contain considerable zinc, which links them up to deposits like La Cueva, in the Bonanza district, where the ores are not associated with lime silicates. The limestone near the intrusion is practically unmetamorphosed except at the very contact of the orebodies; therefore, the earlier barren stages of lime silication, conspicuous at Matehuala, are here practically lacking.[4]

The ore magma illustrated at Aranzazu and at Bonanza evidently contained, besides the metallic sulphides, lime and silica. At Aranzazu, at a depth and temperature relatively greater than at Bonanza (as we may assume), this magma, arising from below, formed lime silicates and chalcopyrite and considerable blende at the contact with limestone; quartz and chalcopyrite, and lime silicates, chiefly, in the monzonite. At Bonanza, with a lower tem-

[4] The Aranzazu deposits have been studied by J. D. Villarello (Congrès Internationale Géologique, 1906, "Le Mineral d'Aranzazu") and especially by A. Bergeat (Bulletin 27, Inst. Geol. de Mex., 1910). The igneous rock which I have designated as monzonite has been called diorite by Rosenbusch, monzonite by Ordoñez, and granodiorite by Bergeat. Bergeat's description of the ore deposits and attendant phenomena is detailed. The wall rocks of the fissure veins in the igneous rock are altered chiefly to uralitic amphibole and pyrite. The igneous rock in general has been altered to garnet by an intense addition of lime (p. 26), and the result is indistinguishable from the garnet rock which is the result of the alteration of limestone. Vesuvianite, diopside, and scapolite are also among the silicates formed. The deposits at Aranzazu (both Villarello and Bergeat agree with my observation) depend on steep-dipping transverse fissures of slight dislocation, which cut the contact. The vein minerals, according to Bergeat's study (p. 93), are chiefly calcite, quartz, wollastonite, green and yellow garnet, chalcopyrite, hematite, blende, and some arsenical tetrahedrite. The most characteristic mineral is wollastonite.

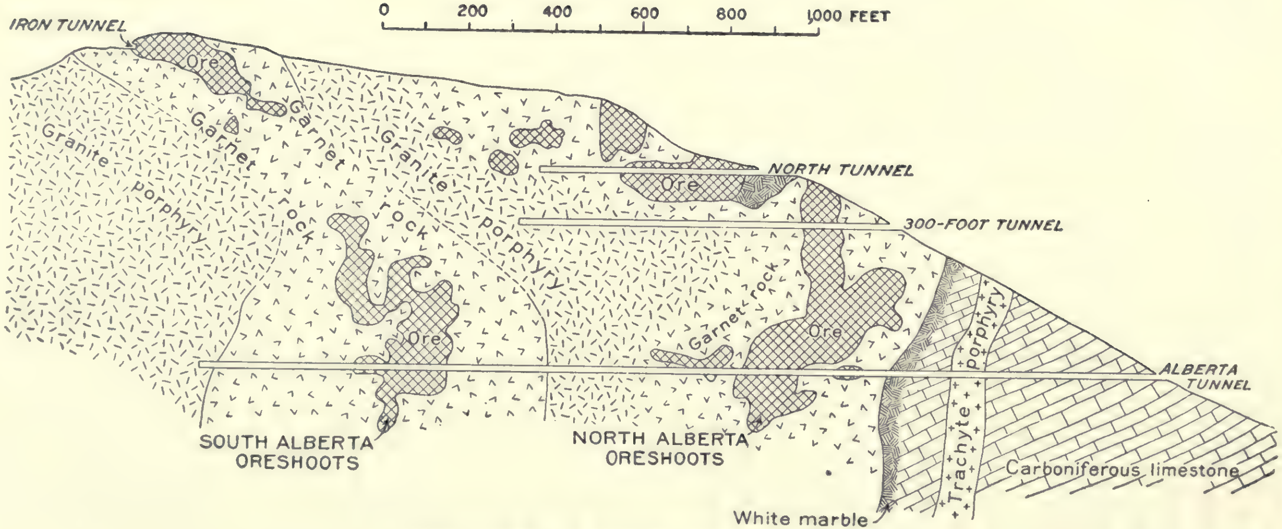
perature, the silica replaced limestone to jasperoid, accompanying galena and some blende. The presence of blende in both ores indicates a similar ore magma in different temperature stages or deposition zones—that at Aranzazu being the deeper.

In this connection brief mention might be made of the White Knob deposit, in Idaho, as described by Umpleby.[5] His section is very instructive (Fig. 101). An intrusion of granite porphyry into limestone shows little or no silication of the limestone at contact—only recrystallization (marbleization); but the granite has been extensively altered to garnet and diopside, in places quite up to the limestone contact; and copper and other sulphides are associated with this alteration. I interpret this case as much like that cited above at Bonanza: the superheated solutions were calcareous and not at all siliceous. Since the White Knob instance is associated with a granite magma, we must admit that the residual solutions were originally siliceous. The examples at Matehuala and Velardeña showed that these siliceous solutions acquired much lime from passage through the limestones; and this was very likely obtained by parting with some of the original silica in exchange. This assumption explains the Bonanza and White Knob solutions, which evidently gave up all their original silica in exchange for the lime of limestones they had traversed, and still remained superheated.

In this we see the origin of the great quantities of barren, non-ferruginous garnet and pyroxene (and other lime silicates) which I have noted as an earlier and singularly abundant stage near many ore deposits, as at Matehuala, Descubridora, and Helvetia (pp. 258, 647, 638); and which I have consistently interpreted as an earlier, higher-temperature stage than the lime silication which was close to sulphide deposition.[6] At Matehuala, I have shown that the earliest solutions contained alumina as well as silica and

[5] *Professional Paper* 97, U. S. Geol. Surv., 1917.

[6] *Econ. Geol.*, Vol. VII, No. 5, 1912, p. 466.



LONGITUDINAL SECTION THROUGH EMPIRE MINE
SHOWING GEOLOGY

FIG. 101.—Cross-section of Empire mine, White Knob district, Idaho. Illustrates, in my opinion, the formation of lime silicates, such as garnet, through highly heated calcic magmatic solutions, whereby the granite, but not the limestone, was attacked. The last magmatic stage was trachyte porphyry. After J. H. Umpleby; Professional Paper 97, U. S. Geol. Surv.; Fig. 2.

lime—no sulphides were deposited at this stage; in fact, the solutions which deposited these pale lime silicates—garnet and pyroxene—extracted iron from the replaced rock. Later the solutions no longer contained alumina, but contained silica and lime, and wollastonite was formed at this period; but still no sulphides were deposited. And only afterward came the deposition of the iron-rich silicates and the closely associated and immediately following metallic sulphides. And finally the solutions contained only lime, and calcite veins were formed. At Matehuala, however, silica was present in all the stages of solutions which formed lime silicates, but at Bonanza and at White Knob it had evidently been entirely eliminated by replacement of limestone in depth. That, in the case of the Bonanza region, at least, this conclusion as to the original silica content of the subsequently purely calcareous silicating solution is correct, is suggested by the conditions at Aranzazu (in the same general magma field as Bonanza), where not only the igneous rock but the limestone has been somewhat altered to silicates, though less than at Velardeña and Matehuala, showing that the solutions in question contained, at this presumably deeper horizon, some silica as well as lime.

Certain phenomena in the Copper Queen area at Velardeña add data to this discussion. In my published article on Velardeña (*Economic Geology,* Vol. III, No. 8, p. 704), I wrote: "The body of quartz-monzonite near the Copper Queen mine is bordered along certain stretches by metamorphic rock; elsewhere there is no contact metamorphism. When metamorphism is present, it has attacked both the limestone and the igneous rock; and frequently the products of the alteration of the two rocks are not distinguishable one from the other. . . . No microscopic examination was made, but garnet, diopside, calcite, quartz, and sulphides were noted as metamorphic minerals. Seams of metamorphic minerals, and also seams of sulphides, penetrate the igneous rock for some distance away from the contact."

The accompanying geological map (Fig. 102) of the Copper Queen surface geology deserves close study. The distribution of the orebodies and the lime-silicate rock now appears to me still more significant than when the map was made, or when I wrote the paper quoted above. Note the long regular fingers or tentacles of lime-silicate rock in the limestone, for example. When I wrote the paper, in

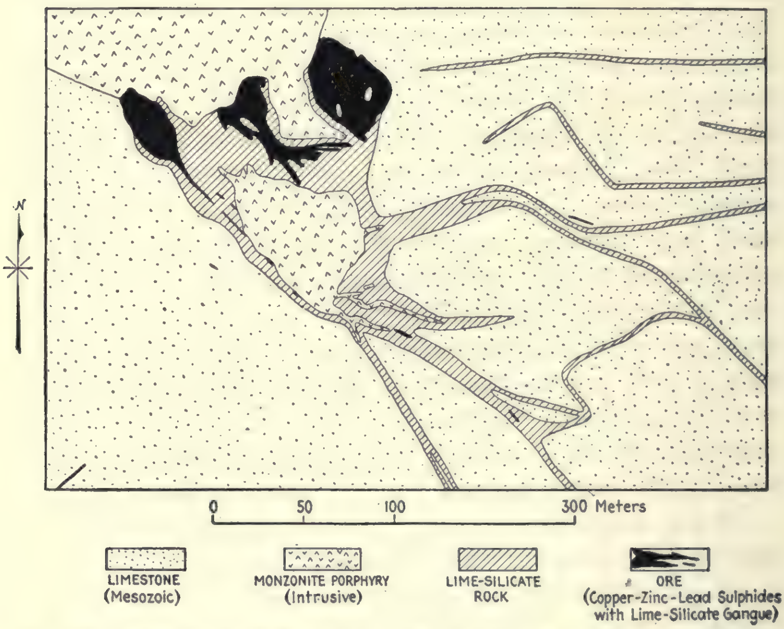


FIG. 102.—Copper Queen mine, Velardeña, Durango, Mexico. Surface geological plan. Geology by G. H. Garrey and M. I. Goldman, under direction of J. E. Spurr, 1907. See text.

spite of the fact that I fully recognized the origin of this lime-silicate rock in part by the alteration of the (granitic) monzonite, I was still, evidently, hidebound by old conceptions. "Replacement" in this case is a better word than "contact metamorphism." The process of replacement, according to the above quotation, has affected the igneous rock as well as the limestone; therefore it was a process subsequent to intrusion. Study of this map not only cor-

roborates the derivation of the lime-silicate rock by alteration of monzonite, but raises seriously the question whether any of the lime-silicate rock shown in this area has been formed at the expense of the limestone. I remember, when I was working on this problem, pondering over the distribution of lime-silicate rock in this area, and trying to account for it, without success, but always accepting as axiomatic that these long tentacles shown in the limestone were formed by the alteration of limestone. But the insistence of this supposed axiom has been completely destroyed by subsequent studies like that recorded for the Bonanza mine; and with this new light I believe it possible that these tentacles may be nothing else than monzonite dikes, altered to lime silicates. This would mean highly heated calcic solutions as the agent which has effected alteration and replacement; and, as at Bonanza, such solutions have acted on limestone only as a crystallizing agent. The sulphide solutions were immediately subsequent. It is evident that both stages of solutions rose along more or less localized or pipe-like channels, for the alteration does not mark the whole contact; but the partial control by fissures is denoted by the veinlike intermittent extension, to the southeast, of the most southwesterly of the three chief ore chimneys.

In the immediate vicinity, however, solutions which produced lime silicates were partly siliceous, as shown by Fig. 103. They were probably not contemporaneous with the calcic solutions indicated in the Copper Queen area, only a few hundred meters distant.

The Descubridora mine, at Descubridora, Durango, Mexico, is another instance of a so-called "contact-metamorphic" deposit, for here limestones have been intruded by extensive bodies of monzonite, with the consequent important development of lime silicates; and here also there are irregular bodies of copper ore on the contact of limestone and monzonite. But this is a superficial explanation. The theory of the "contact-metamorphic" deposit, as formulated by those European geologists who defined

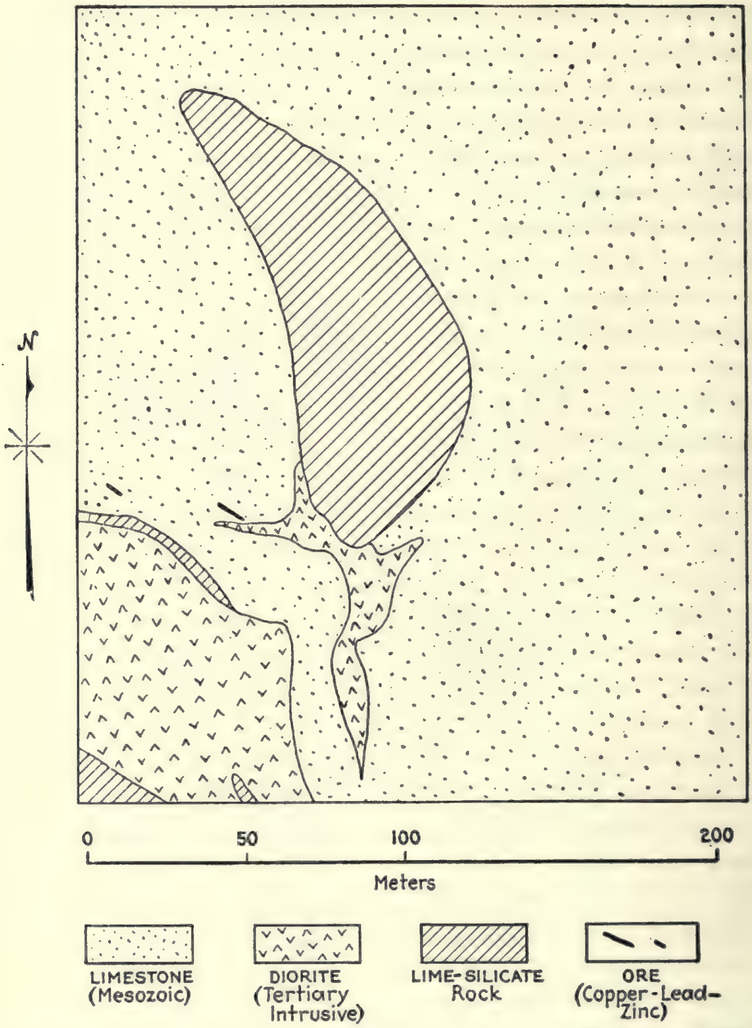


FIG. 103.—Velardeña, Durango, Mexico. Detail of geological map of Copper Queen area. Plane-table survey by G. H. Garrey and M. I. Goldman, under direction of J. E. Spurr, 1907. Illustrates point that lime-silicate rock is not of "contact-metamorphic" origin. Shows independent invasions of (1) diorite; (2) highly heated siliceous-calcic solutions, producing lime silicates by reaction on limestone and diorite; (3) sulphide solutions. In contrast with Fig. 102, where the highly heated solutions which succeeded the monzonite intrusion (only a few hundred meters distant) were probably calcic, the solutions which produced the lime-silicate areas in this figure were probably siliceous as well as calcic, for there is little doubt that the large lime-silicate area shown rep esents the alteration of limestone

the class, is that the vapors emanating from the cooling rock brought the metals into the marginal limestone and replaced this rock with sulphides, and changed the limetone into lime silicates.[7] The study by myself and associates (especially George H. Garrey) of this mine showed the following details:

The monzonite intrusives, which occur as intrusive masses and also as numerous dikes, show the evidence of considerable magmatic differentiation. The normal type is a hornblende-feldspar rock with subordinate amounts of quartz and biotite—probably a hornblende quartz-monzonite.

The texture is granitic, except near the margins and in the narrower dikes, where it becomes porphyritic. Within the main mass are more basic segregations of both fine- and coarse-textured rocks, rich in hornblende, and with no quartz. These in part grade off into the normal monzonite; in part they form angular inclusions in the normal type, showing movement after the differentiation. On the other hand, there are segregations more siliceous than the normal type, which in part grade into the normal monzonite without definite boundaries, and in part occur as small dikes which cut the main monzonite, and which contain little more than quartz and feldspar. Therefore, some of the basic segregations seem to have formed first, at greater depth, and to have been brought up with the intrusive magma; and some of the siliceous segregations were sent up after the intrusion. That they were really subsequent is shown by the fact that they are later than the brown lime-silicate rock which was formed near the contact of the normal monzonite and the limestone, and which consists mainly of garnet, vesuvianite, and probably wollastonite; these lime silicates, however, which are barren of ores, were themselves not contemporaneous with the intru-

[7] See, for example, BEYSCHLAG, VOGT and KRUSCH, translated by S. J. Truscott, London, 1914, Vol. I, p. 351.

sion, but subsequent to it, since they have in part formed by replacement of the monzonite itself.

The ore deposits do not occur associated with the main areas of lime silicates, which, as above noted, are extensive, and probably antedate the metalliferous stages; they are found at places where fissures occur at and parallel to the contact, or where transverse fractures or fissures cut and slightly fault the contact. The transverse fault fissures displace the contact horizontally for distances varying from a few feet up to fifty or more. Some of these fissures originated before or at the time of intrusion, for dikes of the monzonite run out along several of them into the limestone: but later movement occurred along these fissures, and they were used as channels by the mineralizing solutions; and the ore deposition took place mainly on the limestone side of the monzonite contact, and did not extend far into the limestone from the contact. From this we may infer that the metalliferous solutions rose up in the monzonite intrusion, and, therefore, were derived from the magma in depth; and that they were sufficiently aqueous to replace the limestone, and indeed to select this rock preferentially for deposition—in which respect the ore solutions were like those at Matehuala, but certainly different from those which formed the fissure veins in the Terneras diorite intrusion at Velardeña (see p. 716). The primary ores consisted, in the earlier stage, of lean cupriferous pyrite and magnetite, with some reddish-brown garnet, minor amounts of pyroxene or hornblende, some quartz and calcite; at a slightly later stage the silicates disappeared, and the deposit was of massive slightly cupriferous pyrite, and some arsenopyrite, with quartz the principal gangue. Therefore, as at every other "contact-metamorphic" copper deposit which I have examined, the ore deposition took place at and below the critical temperature at which lime silicates can form, and in general at a slightly subsequent period to the main lime-silicate period. The sequence in this district was, therefore:

1. Intrusion of monzonite into limestone.

2. Partial segregation of basic portions, and further upward intrusion.

3. Consolidation at the horizon now exposed.

4. Abundant alteration to lime silicates.

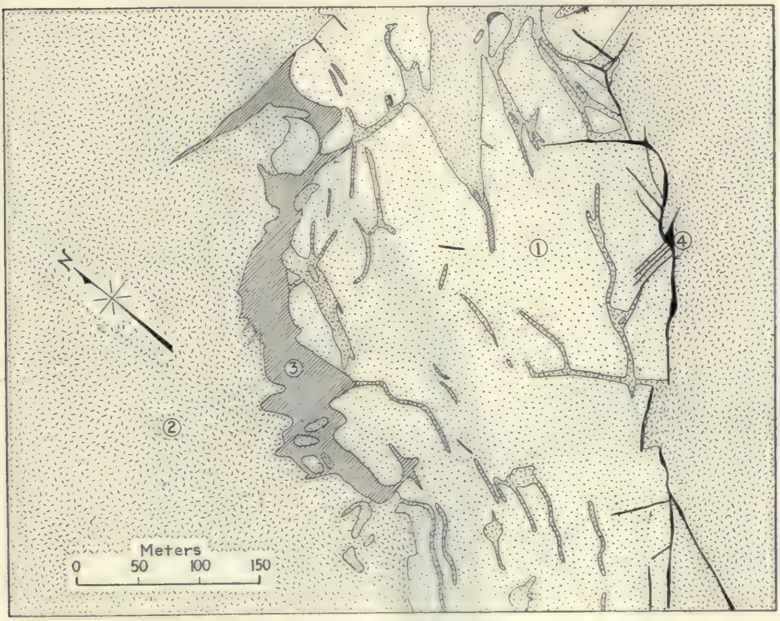


FIG. 104.—Descubridora mine, Descubridora, Durango, Mexico. Portion of plane-table geological survey by J. H. Farrell and W. H. Grant, under supervision of J. E. Spurr and G. H. Garrey. 1, Limestone (Mesozoic), recrystallized; 2, quartz monzonite, intrusive; 3, lime-silicate rock; 4, ore deposits.

5. Formation of fissures parallel to the contact and of transverse slight fault fissures, due to the adjustments of the progressively cooling intrusion.

6. Siliceous dikes—alaskite, grading locally into monzonite types—sent up from the differentiation of the unconsolidated horizon of the intrusion at greater depth.

7. Sulphide magma solutions sent up from differentiation of the unconsolidated horizon of the intrusion in depth,

along fissures; precipitation with some lime silicates as gangue.

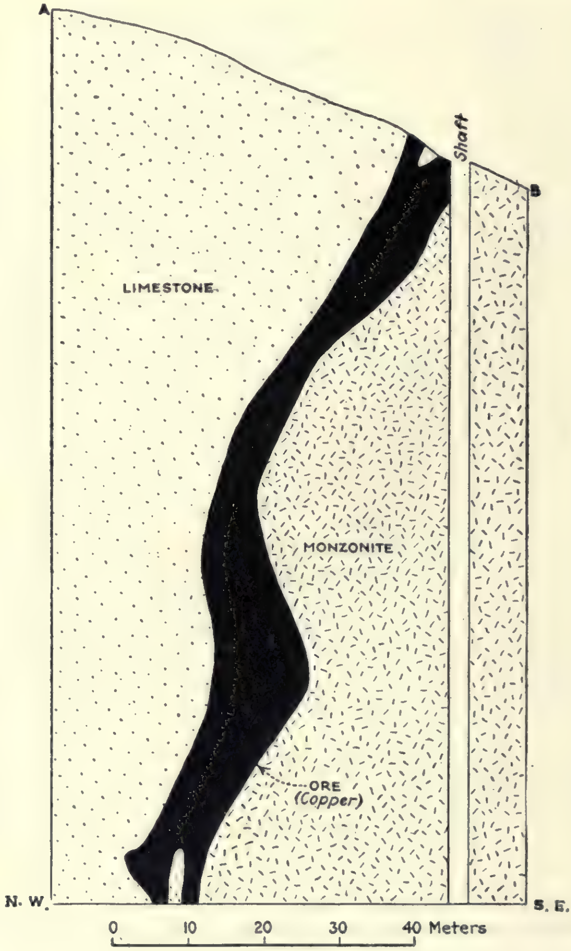


FIG. 105.—Descubridora mine, Descubridora, Durango, Mexico. Vertical cross-section A—B. (See Fig. 106.) Showing orebody at contact, as stoped out.

Fig. 104 shows a portion of a geological map of the mine and vicinity. A belt of limestone some 700 to 800 feet wide is flanked on both sides by the intrusive quartz mon-

zonite. Note the evidence, in the short dikes and fingers of igneous rock in the limestone, that the quartz monzonite also underlies the limestone. Note next that the lime-silicate rock is confined to the west contact of the limestone, and the ore deposits to the eastern side. The west

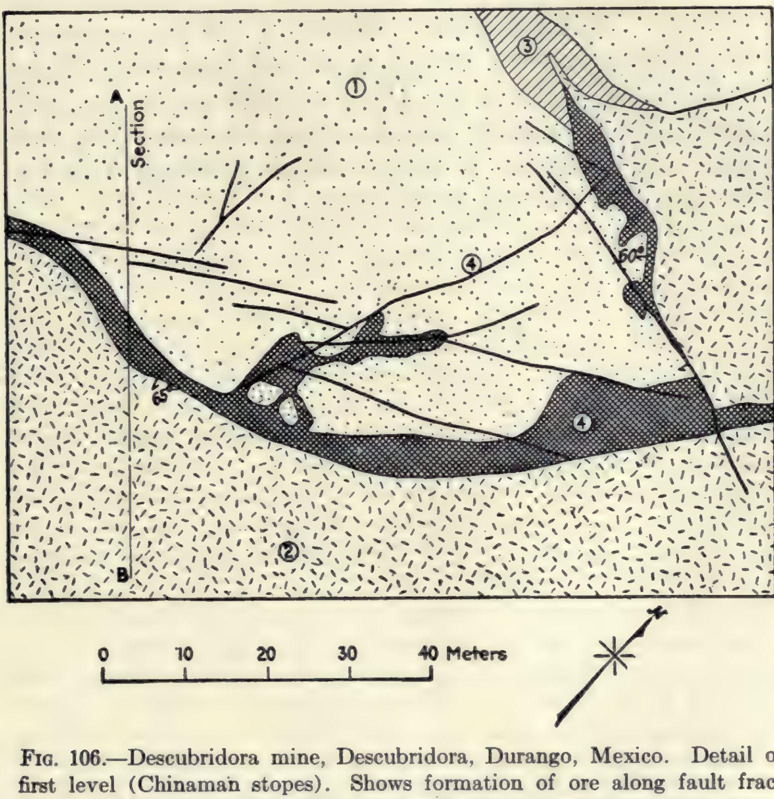


FIG. 106.—Descubridora mine, Descubridora, Durango, Mexico. Detail of first level (Chinaman stopes). Shows formation of ore along fault fractures. 1, Limestone (Mesozoic), recrystallized; 2, quartz monzonite, intrusive; 3, lime-silicate rock; 4, orebodies (copper).

side is quite barren of ore. The recrystallization of the limestone suggests hot calcic solutions.

In this connection note, along the southern end of the western main contact, inclusions of limestone in the monzonite, with no rim of lime silicates. This also suggests that the barren lime silicates were formed by the reaction of hot

calcic solutions on the monzonite, as in the case of the Bonanza mine; and the near-by occurrence of small islands of monzonite in the lime-silicate rock is in harmony with this conclusion. The practical restriction of the lime-silicate rock to the main (west) contact indicates there fissuring and rupturing to provide a special channel for the superheated solutions. The east contact, where the ore lies, is plainly, from its straight lines, a fault contact of later date. Along these contact fissures, and along a transverse set of fault fissures, the ore-magma solutions have ascended. Fig. 105 shows a cross-section of the main mine workings, and Fig. 106 a detail of the first level.

CHAPTER XV

The Precipitation of Ore Magmas

This chapter discusses the variations from the normal pressure-temperature stages of ore deposition, which variations are brought about by the reactions of the ore-magma solutions with various types of rocks or with carbonaceous deposits; or, finally, by the meeting and mingling of unlike types of ore-magma solutions. The precipitating effect of basic rocks upon siliceous-alkaline ore solutions is shown; also the effect of carbonaceous material in procuring the deposition of copper, lead, zinc, gold, vanadium, and other ores. The meeting of different magma solutions brings about premature precipitation and hence orebodies or oreshoots at junctions of fissures, as shown at the Eden mine, in Nicaragua; the Tecolotes mine, in Mexico; and the Silver Lake mine, in Colorado. On the other hand, different ore-magma solutions, following normally one upon the other, do not usually create enrichments or oreshoots even at the intersection of branching fissures: for the precipitation of one is complete before the next solution arrives, and the solutions themselves do not meet. The Pony Express mine and the Camp Bird, both near Ouray, Colorado, are examples.

Wide quartz veins carrying gold and silver, at Aurora, in Nevada, show some enrichment in the field near the junction of branches, indicating slightly differing solutions flowing along different fissures, and meeting at junctions. But rich streaks in these veins, and on the vein walls, also originate in another way, which can only be explained by magmatic differentiation in the siliceous vein-magma; and I appeal to the principle of differential gaseous tension to account for this, just as I do for the transfer of metallic sulphides in general from magmas to the periphery, or indeed for the differentiation of igneous rocks one from another.

IN THE PRECEDING CHAPTERS I have discussed the precipitation or crystallization of ore-magma solutions as a simple function of temperature and pressure. This is, I may now point out, on the assumption of homogeneous wall rocks, and no interference with the

ore-magma solutions by other solutions. Where this homogeneity and lack of interference exist, there is still great variation and complexity in the temperature-pressure conditions, as I have described in many places in the preceding pages. But having grasped this temperature-pressure complexity, we have next to recognize the fact that the rocks through which the ore-magma solution passes are in many cases not homogeneous, and also that there is the possibility of meeting other solutions. If we consider the heterogeneity of wall rocks for the moment, from the basis of chemical heterogeneity only, and regard the rocks as solid solutions, as they are termed, and as they function, physicochemically, we can group them and the fluid solutions which we more familiarly regard as such, and discuss the chemical reactions of ore-magma solutions with the rocks and other chemically different substances which they encounter. Such reactions, if they take place, may, of course, determine the precipitation of the ore magma, or of certain elements in it, at a different time, and, therefore, at a different place, from what would be normal were the wall rocks homogeneous.

For the subject which I am broaching there appear to me to be, from the chemical standpoint, five chief groups of rocks, which all serve as wall rocks to orebodies: three sedimentary—purely siliceous rocks (sandstones and quartzites), basic and often carbonaceous rocks (shales), and purely calcareous rocks (limestones); and two igneous—the siliceous-alkaline group and the basic or lime-magnesia-iron group. By interpolation and variation from these five types we shall obtain (for our purposes) most known wall rocks.

For an effective chemical reaction we need a meeting of unlike solutions. Therefore, the siliceous-alkaline-sulphide ore-magma solutions characteristic of derivation from siliceous and intermediate magmas, we may suppose, would be modified to the point of precipitation, not so much by the siliceous-alkaline igneous rocks and the quartzitic sedi-

mentaries as by the other three chief groups. In general, a glimpse over the whole field indicates that this rough rule will hold. The dark silicates of the igneous rocks and of the shales, and the metallic minerals of these rocks, are known from many observations and experiments to have the property of precipitating preferentially the ore solutions. Examples of this type are numerous, and the principle is too well known to need the mention of any. It is in part this relation that has caused many ore deposits to be referred for their origin to the basic magmas, or to leaching from the basic rocks, when these acted only as the precipitant. The reactions, however, differ for different metals. Thus the siliceous-magma-derived gold-quartz veins of many districts have been often referred to this origin (from basic igneous rocks), because in many cases they are associated with diorite or diabase dikes which are one of the differentiation phases of the parent granitic magma. Copper is notably thus precipitated by basic igneous rocks, as I have observed at Ray, Arizona (p. 384). Silver is similarly affected, strongly and in many instances.

We may broadly group the effect of the dark silicates and the sulphides of the basic rocks and of the shales, with the carbonaceous matter of the shales, for all act as precipitating agents. Organic or carbonaceous matter has some special precipitating influences of its own, tending not only to precipitation but also to reduction. Thus at Aspen, as I have described, rich silver sulphides have been reduced to native silver by the action of carbonaceous shales which form one of the borders of the orebodies. Also, I have inferred the same process at Breckenridge, Colorado, for the splendid development of native gold in shales. A specially interesting problem is the association of asphaltite and vanadium in Peru. Dikes or veins of asphaltite (between gilsonite and grahamite) carry around 1 per cent (more or less) of vanadium; and selected material 4 to 5 per cent, so that the ash of this selected stuff would run

15 to 20 per cent vanadic oxide (V_2O_3),[1] although it is likely that the original form was a sulphide. The ore of the famous Minasragra mine, the richest vanadium property in the world, is considered by Hewett[2] to be "an extreme phase of differentiation from asphaltite." The ore in this mine occurs along a fault zone, and belongs to a geological period of igneous activity and rock differentiation, as is shown by the occurrence of diabase (in part olivene-bearing), andesites, and quartz porphyries, near the mine. The quartz porphyries, according to Hewett, are nearly contemporaneous with the fault fissure along which the ore formed. From the general parallelism of the asphaltite deposits of the whole region to the line of contact between the sedimentary rocks (Jura-Triassic and Cretaceous) and more recent eruptive rocks, there is little question that the asphaltite veins in general have, as one of their main determining genetic factors, the igneous rocks. The vein at Minasragra contains vanadium sulphide (which has been experimentally formed at a temperature of about 400°), iron-nickel sulphide (bravoite), a black hydrocarbon or asphaltite (quisqueite), and coke. The coke lies next the sulphide-bearing portions of the vein, the uncoked asphaltite further away, at least in one of the sections shown by Hewett; although in the sulphide portions of the same vein, asphaltite, coke, and patronite (vanadium-iron-nickel sulphides) are finely intermingled.

The occurrence of vanadium in the ash of the asphaltite veins suggests at first that the asphaltite has acted as a collector or solvent, rather than as a precipitant of the vanadium.[3] The peculiarities of the vanadium-rich phase at Minasragra, however, indicate to me that the original vanadium solutions were hot magmatic solutions, foreign to the asphaltite, since they appear to have partly coked

[1] J. G. Baragwanath, *Eng. and Min. Jour.*, May 7, 1921, pp. 778-781.
[2] D. F. Hewett: *Trans.* A. I. M. E., Vol. XL, 1909, p. 298.
[3] J. F. Kemp: *Trans.* A. I. M. E., Vol. XL, 1909, p. 863.

it,[4] and since the sulphides are not uniformly distributed through it. That these magmatic solutions were basic-magma-derived, I believe to be proved by the presence of nickel sulphide. Vanadium occurs in the titaniferous magnetites (which are usually associated with pyroxene-bearing basic igneous rocks), and from its occurrence has been considered by Kemp, Hillebrand, and Washington to have its home in the moderately basic eruptives. Olivene diabase is one of the associated rocks at Minasragra. Considering this evidence of a magma-derived metallic solution differing in temperature and in composition from the asphaltites, together with the general presence of vanadium in the asphaltites of the region, the conclusion that the asphaltite secured its vanadium content by fixing it from magmatic emanations seems clear to me; after having thus incorporated it as one of its constituents, the vanadiferous asphaltite in many places migrated far along fissures. That bituminous matter does so fix vanadium is shown by the occurrence of the metal to the extent of over 1 per cent V_2O_5 in a stratum of black carbonaceous shale in Peru,[5] and its occurrence in the United States, not only in asphaltites[6] but in various coal beds. The chief vanadium-bearing province in the United States, in southwestern Colorado and eastern Colorado, is in Jurassic sandstones containing partly carbonized wood, with which the ore is often associated. The micas (roscoelite or vanadium mica,

[4] Coking takes place at as low a temperature as 400° C. and from there on as high as 1,200° or so. In view of the fact that the asphaltite is only partially coked, although it probably cokes easily, it is likely that it did not experience much more than the minimum temperature—that is to say, not much over 400°, or, say, 400 to 500°. This checks with the experimental formation of vanadium sulphide at 400° given above, and indeed pretty well with other clews as to the temperature under which ore deposits are formed. I have surmised on various grounds that the range of deposition of the sulphide ore magmas of the intermediate and siliceous-magma series was from below 575° down to around 365° (Chapter XVIII, p. 796, Chapter V, p. 263); and the same appears to hold true of the sulphide magmas derived from basic magmas.

[5] *Eng. and Min. Jour.*, May 7, 1921, p. 781.

[6] D. F. HEWETT: *Trans.* A. I. M. E., Vol. XL, 1909, p. 297.

and mariposite or chromium mica) of these Colorado ores indicate to me an elevated temperature and magmatic solutions, and the replacement of quartzite in part by these ores suggests a non-siliceous, basic-magma-derived type of solution. The conjunction of a vanadiferous metallographic province from whose magmas vanadium is given off, and carbonaceous materials—preferably hydrocarbons—as precipitant, seems to be the combination necessary for the concentration of commercial vanadiferous ores in general.

Vanadium is not the only metallic mineral in Peru which is associated with bituminous material, although it is by far the most striking. At Huancavelica, which is in the same general region of Peru as the vanadium deposits, there are cinnabar (mercury) deposits, which are impregnations in clean porous sandstones,[7] where the cinnabar is usually associated with a black or dark bituminous substance, pyrite or marcasite, galena, and a little realgar. It is a region of igneous rocks, with still active warm springs. In this case, whence the bituminous substance? If the cinnabar and the realgar is mainly a gaseous-aqueous deposit from the igneous magma below, is the bituminous substance of the same origin? Whether we assume that or whether we assume that the bituminous substance has been distilled out of sedimentary rocks by the heat of igneous intrusions, we must agree that its migration and deposition were due to igneous causes. Here is an association and a deduction which may help to explain the puzzling occurrences of another bituminous substance, petroleum, in the Gulf Coast region of the United States and Mexico.

The association of bituminous material in Peru with mineral deposits of such diverse origin, nature, and probable mode of separation from the magma, as vanadium and mercury (though both are doubtless magmatic), gives weight to the assumption that the metalliferous-bituminous material is indeed in each case the result of mixture rather

[7] J. T. SINGEWALD: *Eng. and Min. Jour.*, 1920, Vol. 110, p. 518.

than having any common origin, and that the bituminous matter has been distilled by the igneous intrusions out of the sedimentary rock into fissures, where it has mingled with magmatic solutions or exhalations. Bituminous material is common in cinnabar deposits, as in California and in Jugoslavia. It is likely that bituminous material, thus mingled with metallic magmatic solutions, may eventually and at a lesser temperature act as the precipitant of the metals; and possibly, therefore, the presence of such material in mercury deposits may indicate that this highly volatile metal has been precipitated in workable quantity best by such means, whether the bituminous matter was carried along with the solutions or encountered in the rocks.

Granted, however, the mingling of bituminous material distilled from the sedimentary rocks into fissures, with magmatic metal-bearing solutions, as instanced by the vanadium and mercury deposits of Peru, and the mercury deposits elsewhere, we have a likely explanation of other puzzling cases. Such a case is presented by the graphite impregnations of the wall rock of the vein at Silver Islet, Ontario.[8] The ore is of a character much like that at Cobalt, containing silver, nickel, cobalt, arsenic, copper, lead, and zinc: the main bonanzas were "accompanied by a strong impregnation of graphite" in the walls, which are pre-Cambrian beds cut by a dioritic dike. The fact that the walls of the bonanza here were impregnated with graphite, evidently derived from the ore solution, indicates the separation of the bituminous substance on consolidation of the metallic minerals (which was perhaps brought about in part by this very precipitant) and a driving of it into the wall rocks. The graphite, of course, shows in this case a higher-temperature vein deposition than the bituminous matter of the quicksilver deposits.

The sulphide deposits at Ducktown, Tennessee, contain

[8] WILLETT G. MILLER: Report of the Ontario Bureau of Mines, 1905, Part II, p. 55

graphite.[9] These deposits contain metallic sulphides and oxides, pyrite, pyrrhotite, chalcopyrite, zinc-blende, specularite and magnetite; and as gangue minerals, besides graphite, actinolite, tremolite, pyroxene, garnet, zoisite, chlorite, mica, titanite, and feldspars. All are said to be of "practically contemporaneous crystallization,"[10] but a series of stages marked by falling temperature is to my mind marked by both metallic minerals and gangues—the gangue minerals starting with feldspars and mica, through garnet and pyroxene to actinolite and tremolite, thence to quartz and calcite; and the metallic minerals from specularite and magnetite, through chalcopyrite and pyrrhotite, to zinc-blende. The temperature of such a combination varies on both sides of the critical temperatures between lime silicates and quartz and calcite, and between pyroxene and amphibole (see p. 263) or both above and below 500° C. These deposits are in a sedimentary series of conglomerates, sandstones, and shales.

Passing from these veins into quartz veindikes of the pegmatitic type, and to pegmatite veindikes themselves, we find graphite in some of them; and I believe that the above explanation of the origin of the bituminous matter associated with veins in Peru, and inferentially of the graphite at Silver Islet and Ducktown, will apply satisfactorily also to these pegmatitic graphite veins. In Ceylon, graphite-bearing fissure veins (veindikes) cut a crystalline series of metamorphosed sediments. These veindikes contain mainly graphite, with a little pyrite and quartz, and occasional biotite, orthoclase, pyroxenite, apatite, etc. They have sharp walls, and impregnate the wall rocks with graphite. Most of these graphite-bearing veins, according to the literature, occur in regions of graphitic sediments[11]; and in regions of graphitic sediments there is

[9] J. F. Kemp: *Trans.* A. I. M. E., Vol. XL, 1909, p. 863.

[10] W. Lindgren: "Mineral Deposits," Second Edition, 1919, p. 753.

[11] E. S. Bastin: *Econ. Geol.,* Vol. VII, No. 5, Aug., 1912, p. 419 *et seq.* T. H. Clark: *Econ. Geol.,* Vol. XVI, No. 3, Apr.-May, 1921. "The Origin of Graphite," p. 107.

proof that the carbonaceous material has been fluid, and so mingled with solutions that deposited the metamorphic silicates[12] by recrystallization from the original materials of the sedimentary beds (Fig. 107). In the fluid condition here indicated, the bituminous or carbonaceous material (which here appears to be probably of organic origin) might be drawn off into fissures, and, meeting a pegmatitic magma solution, mingle with it in various proportions. Certainly, the lack of graphite in quartz and pegmatite veins except in

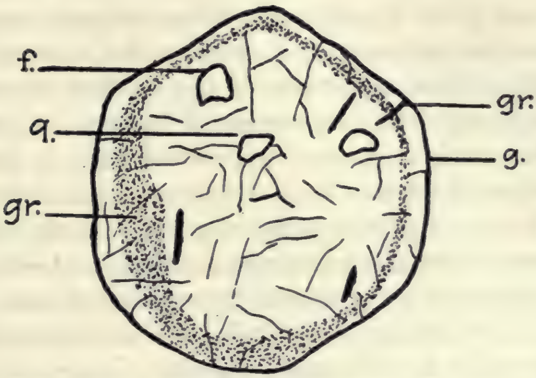


Fig. 107.—Graphite inclusions in garnet crystal in graphite gneisses; Sleaford Bay, South Australia. g, Garnet; gr., graphite; f., feldspar; q., quartz. The aureole of fine graphite (gr.) flakes near the margin of the crystal indicates the deposition of graphite from solution. After C. E. Tilley: "Economic Geology." Vol. XVI, No. 3, p. 192, Fig. 20.

a few localities tends to indicate some non-magmatic conditioning circumstance, and this appears to be fulfilled by the graphitic schists which they cut. The hypothesis that the carbon is derived from the freeing of carbon dioxide from limestone, during the process of silication, and the subsequent deoxidation of the carbon dioxide to form graphite,[13] is probably not sound, for the very good reason that graphite only very exceptionally attends this process of contact silication.

[12] C. E. Tilley: *Econ. Geol.,* Vol. XVI, No. 3. "The Graphite Rocks of Sleaford Bay, South Australia."
[13] *Ecom. Geol., loc. cit.,* p. 182.

Passing now back again from the deep-seated and ancient graphite-bearing veindikes to consideration of relatively recent asphaltite dikes, especially those near igneous contacts, as in Peru, which plausibly owe their origin to the distilling effect of the igneous heat combined with the creation of fissure zones by the intrusion: it is clear that, in bituminous beds, igneous heat and the penetration of hot magmatic solutions might be able to accomplish a migration and concentration of petroleum. This may explain the frequently observed connection of petroleum with volcanic centers, and great deposits of sulphur, and salt waters, and sometimes hot springs; and perhaps the connection with the puzzling dome structures of the Gulf of Mexico coast and elsewhere. The occurrence of helium in connection with other natural gases (and petroleum) is not to be explained on an organic basis, for this is a gas due to radioactivity and so is probably an emanation from the depths.

The same type of carbonaceous precipitant—carbonized wood—which has precipitated the vanadium ores, in part at least, in Colorado and Utah, has precipitated copper and silver also, in this same region. Copper is thus, in the vanadium metallographic province, precipitated locally with vanadium; elsewhere without it. In Texas, copper as covellite, chalcocite, and chalcopyrite has been precipitated by strata rich in plant remains, and by fossil wood in Permian sandstones and shales; and at Silver Reef, in Utah, argentite and native silver have been deposited in Triassic sandstones rich in plant remains. Note not only the precipitative effect of the carbonaceous matter, but the reducing effect, in the production of native silver, and the precipitation of the relatively sulphur-poor copper sulphides, such as chalcocite. Similar deposits are found in Europe, and include not only copper and vanadium but some lead and zinc. In the Upper Mississippi Valley, a bed of oil shale at the top of the Trenton (Ordovician) has caused precipitation of lead and zinc sulphides, according to Bain. In Virginia and Tennessee, lead and zinc ores

occur especially where the limestones are bituminous. In Southwestern Missouri there is much organic matter associated with the lead and zinc ores, and asphaltite has been noted;[14] and in the Oklahoma (Miami) zinc field bitumen is very abundant in association with the ores. In the gold-quartz veins of Victoria, in Australia, gold has been precipitated by beds of black carbonaceous shale at their intersection by quartz veins.

In short, organic material, and especially carbonaceous beds, constitute a very important and effective precipitant.

Limestone reacts very powerfully with some ore solutions, and a process of replacement goes on; metallic sulphides and silica replace, molecule for molecule, the limestone, which is carried away; or at a relatively elevated temperature silica combines with the limestone to form lime silicates, with a very free addition and subtraction of elements, varying with the stage and phase of alteration. It is to be expected that limestone would react very powerfully to the siliceous-magma- and intermediate-magma-derived ore solutions and other emanations, since these are siliceous-alkaline, and not predominantly calcic; and, indeed, this is the case, as the deposition of ores and the formation of silicate gangues on and near the contact of siliceous or intermediate igneous rocks and limestones shows. Lead, zinc, and copper are the most conspicuous deposits caused by the reaction of the ore-magma solutions with limestones, or by "replacement" of limestones.

Gold deposits replacing limestones are rare, but where they do occur are apt to be of low grade and of limited amount, as at Inde, in Durango, where I have studied them, as well as at Mercur, in Utah, and Manhattan, in Nevada. Lead and zinc deposits most characteristically do not occur at the contact with large bodies of intrusive igneous rocks, but in a zone more remote from this contact, with or without association with dikes, which also form part of the aureole of the main intrusive. Such replacement deposits

[14] J. F. Kemp: *Trans.* A. I. M. E., Vol. XL, 1909, p. 861.

are very important. They are generally argentiferous, as at Leadville in Colorado, and Eureka in Nevada. In many of these instances the solutions from which they formed are recorded as having been siliceous, from the replacement of the limestone to form jasperoid,[15] a fine-grained replacement silica rock, as I have described at Aspen and at Leadville. A selective precipitation usually takes place, whereby the sulphides tend to be precipitated in a massive way without a large proportion of intermingled quartz, and the bulk of the silica is deposited further away from the focus of deposition, forming in many cases thick envelopes or jackets for the orebodies.[16]

Very important is the precipitating effect, on ore-magma solutions, of the mingling with other solutions. The strange case of the mingling of bituminous or petroliferous fluids with ore solutions, inferred above for Peru and elsewhere, is only an extreme example illustrating the mingling of various solutions which must take place.[17] Sometimes magma ore solutions representing slightly different stages, traveling along separate fissures, and doubtless proceeding from distinct sources although from the same general magma, may meet and mingle. The result of any such mingling is apt to be precipitation. An excellent example of this is in the gold-quartz veins of the Eden mine, in the Pispis district of Nicaragua, and I will instance this more in detail.

The veins in the Pispis district are in Tertiary andesite, which constitutes the sole rock of the district so far as I have observed. In the Eden-Bonanza end of the district there are two sets of veins running at right angles—north-south and east-west; both dip steeply—70 to 80°. There

[15] Investigations by Spencer (*Professional Paper* 96, U. S. Geol. Surv., p. 63) of fluid inclusions in a jasperoid at Ely, Nevada, indicated a probable temperature of formation of 200 to 350° C. Jasperoids, however, probably form over a wide range of temperatures.

[16] *Monograph* XXXI, U. S. Geol. Surv., p. 220 *et seq.*

[17] For a still stranger case, of the mingling of ore magma and rock magma, see Chapter XVI, p. 763.

are also two *kinds* of veins, representing distinct periods. One kind consists mainly of sulphides, with a moderate amount of gray quartz. The sulphides consist of pyrite, chalcopyrite, galena, and blende, and carry gold—in the better portions of the vein, from $10 to $20 per ton. The gold is the only metal recovered. The ore is sometimes finely banded. These veins are usually not over five to six feet wide. The other kind is of white barren quartz, containing practically no sulphides and a very little gold. By itself, this type of vein is rarely, if ever, profitable, for the gold contained is probably not over $2 or $3 per ton. These veins are wide and persistent—often 20 to 40 feet wide. As to relative age, I assume that the sulphide veins are the younger. Nearly all of the big quartz veins run north and south, while the small auriferous sulphide veins run both north and south and east and west. Here we have the typical evidence of fractional crystallization or differentiation of the siliceous ore magma into the low-grade quartz, and the sulphide magma. The quartz, as the big white veins indicate, was injected in dike-like bodies, without banding, and, therefore, probably relatively dry; while the sulphides, unlike the quartz veins, formed largely by replacement of the crushed andesite, and by this as well as by the frequent fine (rhythmic) banding indicate the more aqueous magma.

As to these sulphide veins: east-west veins and north-south veins of this type do not differ. Where they cross, sometimes one, sometimes the other, is the later, and there is no enrichment at their junctions. But take a representative vein of either the east-west strike or the north-south strike. We find that besides the main fracture lines which determined the veins, which are fairly straight, there are branching fractures, usually diverging 25 or 30° from the main fractures; and that the vein filling has formed along these branches as strongly as along the main fractures, and frequently much more strongly, so that in drifting on the vein and following the widest stringers, the course of the

drift will often suddenly turn this angle of 25 to 30° or so. Now, when this occurs, a change in the value of the ore is likely to take place; in other words, these intersections have procured enriched ore deposition and indeed have determined the oreshoots; and the branching veins are "feeders," or "vein robbers," according to the point of view —the former, if you are passing from the barren vein to the ore, the latter if you are passing from the ore to the barren vein; in other words, speaking in the colloquialism of the day, according to whether you are coming or going.

Where such a branching occurs at the end of an orebody, it is rather characteristic (and this on both the east-west and the north-south veins) that the diverging branch shows the stronger vein, though barren of gold; while the direct linear continuation of the ore is apt to be a much smaller, and quite as barren, stringer. It has been noted that the stronger branch is as rich in pyrite and chalcopyrite and quartz as is the ore; but that the ore (in the vein formed by the combined branches) is distinguished, in addition to the above minerals, by galena, blende, and gold. Here there is evidence—for the above is found repeatedly—of different solutions, of two types, but contemporaneous, moving along separate fractures, and forming the ore by their mingling. One solution certainly carried silica, iron, and copper, sulphur, and a little gold; probably it also carried zinc and lead. It is not quite clear what the other fissures carried, but certainly a cooler solution. At any rate, when the two solutions met, lead, zinc, and gold were thrown down, but not otherwise. Since the barren (carrying, say, $1 in gold) pyrite-chalcopyrite-quartz veins are stronger and more persistent, we may conclude that conditions were near the critical temperature for the precipitation of these minerals —say near the critical temperature of copper deposition, and so above the critical temperature for lead-zinc deposition; but a mingling of the solutions brought down the latter also, by reducing the temperature. Which solution carried the gold, or if both did, is open to question: at any rate, the

mingling of the two types of solutions brought about its precipitation along with the sulphides.

The above rather constant features of these veins may be seen both in a horizontal and a vertical section, as, for example, in the Eden mine. This peculiarity, however, is to be noted: on a horizontal plan the ore goes quite up to the branching (Fig. 108), or frequently goes out a little way on each branch; on the vertical plan, however, as seen in the Eden (Fig. 109), branches converging upward produce ore deposition at the junction, but the deposition gains strength upward from the junction, and is in full strength

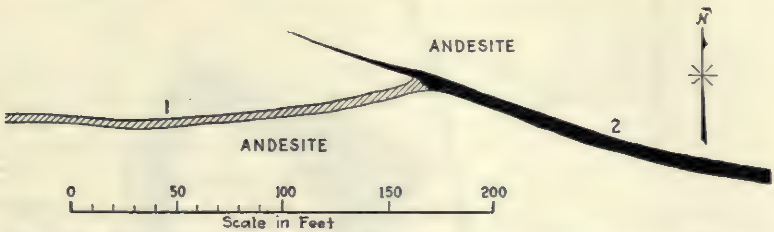


Fig. 108.—Eden mine, Nicaragua. Plan of portion of Culebra vein, Culebra tunnel level. Fissure vein in andesite. 1, Quartz, pyrite, chalcopyrite; no galena and blende; no gold; not over three feet wide; not pay-ore. 2, Galena, blende, pyrite, chalcopyrite; average one-half ounce gold; over five feet wide; main oreshoot. Illustrates ore deposition through confluence of different types of ore-magma solutions.

only some 40 to 50 feet above. *This shows an upward flow of the ore solutions.*

We can learn a lot as to the nature of ore-magma solutions and as to the method of ore deposition from the phenomena accompanying intersection. I have said above that the north-south and the east-west veins, which run at right angles, and which cross without faulting one another, are quite similar; and that there is no enrichment at their intersection. Yet while these two sets of veins were contemporaneous, they were not quite simultaneous. They are not confluent at intersections—one crosses the other, but sometimes it is an east-west vein which crosses a north-south one, and sometimes the reverse. Evidently it is

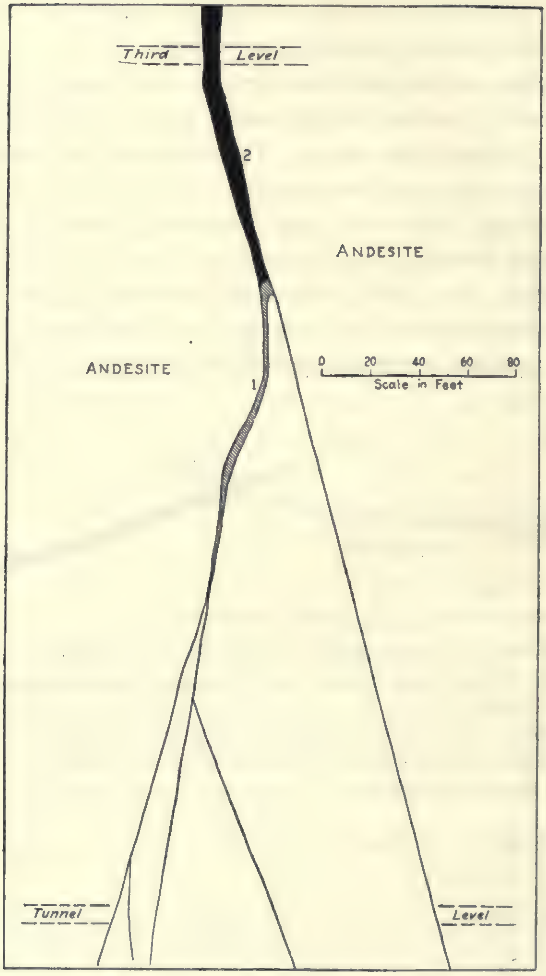


Fig. 109.—Eden mine, Nicaragua. Vertical cross-section of portion of Eden vein; a fissure vein in andesite. 1, Quartz, pyrite, and chalcopyrite; no galena or blende; no gold; not over two and one-half feet wide; not pay-ore. 2, Galena, blende, pyrite, and chalcopyrite; average around one ounce gold; about six feet wide; main oreshoot. Illustrates ore deposition through confluence of different types of ore-magma solutions, showing on a vertical section the same as Fig. 108 of the Culebra vein does on a horizontal section. The present vertical section indicates ascending ore-magma solutions, uniting above.

because they are not confluent that there is no enrichment at the intersections, as there is in the case of the branching veins, of both east-west and north-south sets, which are confluent. The sharp suddenness of the injection of these ore solutions is thus strikingly shown: the two main veins of the Eden mine, for example, the Eden and Culebra, running at right angles, meet, but without creating an ore-shoot thereby. There was, therefore, a brief time difference between the filling of these two principal veins; but the same two types of aqueous ore-magma solution were seeking admission to the fissures at both events.

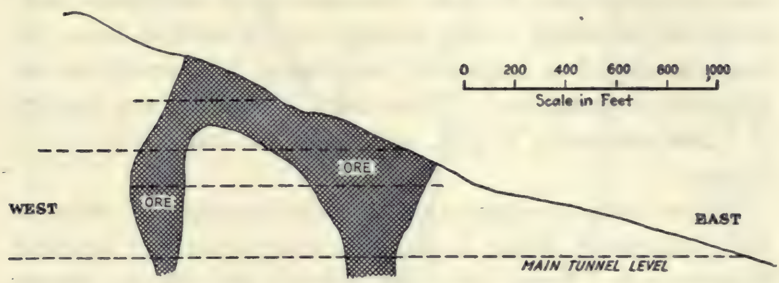


FIG. 110.—Eden mine, Nicaragua. Section on plane of Culebra vein, showing oreshoots. Illustrates widening upward and emerging above of oreshoots. Except very near the surface, ores are primary sulphides, with uniform values to deepest level.

The orebodies on these veins have the characteristic limited vertical extent of the Tertiary veins in volcanic rocks; the accompanying vertical projection (Fig. 110) of the developed orebodies on the Culebra vein shows that the plane of the surface has cut the central or lower part of the orebodies, and that they diminish rapidly in extent in less than a thousand feet in depth.

The Tecolotes mine, at Santa Barbara, Chihuahua, Mexico, which I examined in 1907, is, like the Eden mine, an excellent example of the result of two distinct chemical types of ore-magma solution, contemporaneously flowing through the rock, and, when they have flowed along distinct fissures which converge and unite, causing by their mingling

the precipitation of orebodies along the trunk vein where they have mingled. The Tecolotes veins are strong fissure veins, in shale on both walls. Such igneous rocks as I noted in my brief investigation are later than the veins. Dikes of younger rhyolite cut the veins; and long afterward there came a thin surface flow of andesitic lava, forming a "capping." The veins run in general northwest. There is a strong trunk vein—the Coyote—which receives a number of strong branches from the northeast side, of which the principal are called the Tecolotes and the San Albino veins and a smaller one the Rica vein (Fig. 111). A number of branches also come in from the opposite or southwest side, but these, although visible enough on the surface, have not been developed underground, and hence, I inferred, are not valuable or promising. These veins altogether are upward of 1,200 meters in length, and I do not know how much longer.

The orebodies are plainly due to the junctions of different vein branches. When I came to investigate the different branch veins, I found that they fell into two distinct classes mineralogically. To one class belong the Coyote (the trunk vein) and the Tecolotes (one of the branches coming in from the northwest); to the other the San Albino and another lesser branch, the Rica, also coming in from the northwest. Both classes have the same general appearance, being galena-blende veins with comparatively little pyrite and with quartz gangue. But there are certain marked and constant differences. The veins of the first class have a gangue consisting almost entirely of quartz, while the San Albino has, typically, considerable fluorite, contemporaneous with the quartz. Ores of the second class (San Albino) are higher in gold, and while the amount of silver is about the same as in the better portions of the Coyote and Tecolotes veins, the amount of lead is less, so that the proportion of silver to lead is distinctly greater. Again, the proportion of zinc to lead is less in veins of the second class. In the San Albino, there is probably twice as much lead as zinc;

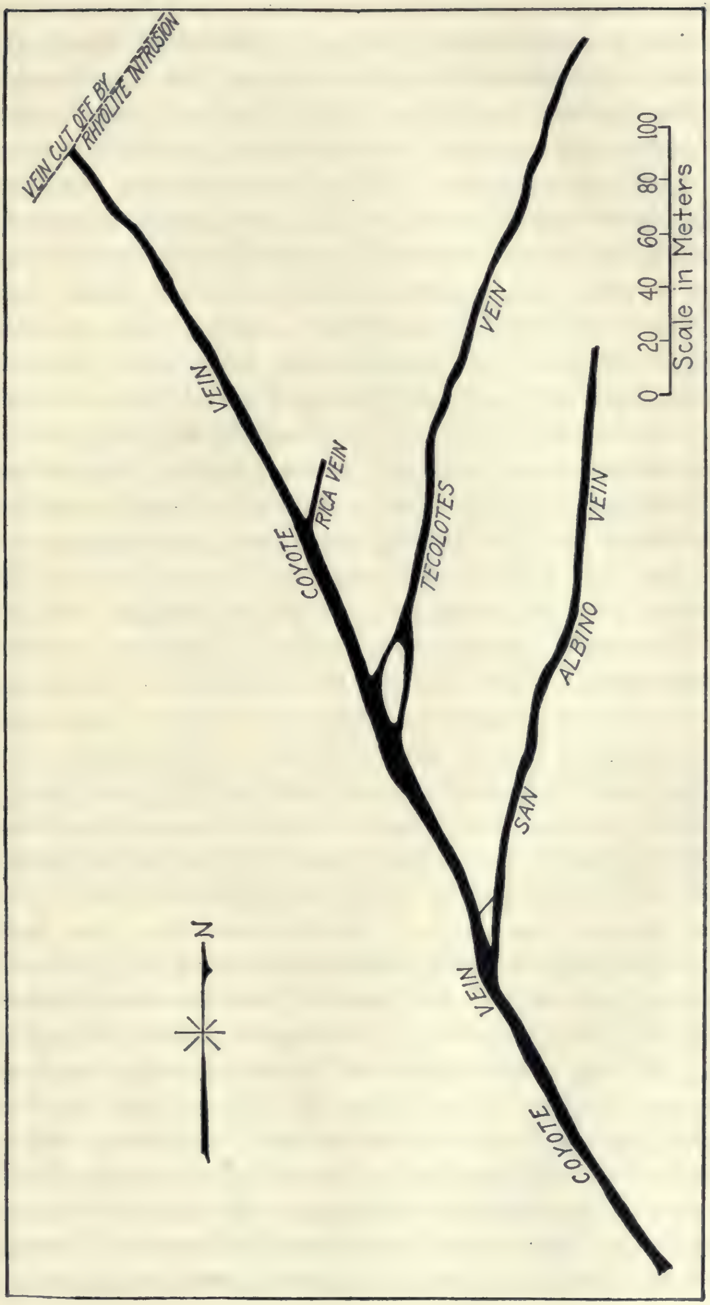


FIG. 111.—Veins in Tecolotes mine, Santa Barbara, Chihuahua, Mexico, as partly developed on the sixth level. See text.

while in the best portions of the Coyote and Tecolotes the amounts are about equal, and away from these shoots the zinc is, on the average, largely in excess. At first the distinction between the San Albino type and the Coyote-Tecolotes type suggested a different age for the two; but on examination the facts did not bear this out. The San Albino joins the Tecolotes vein, in the section above the fourth level; below the fourth, it joins the Coyote. In both cases a wide and valuable orebody on the larger vein (Coyote or Tecolotes) marks the junction with the San Albino; moreover, ore extends also back along the San Albino from the junction, forming a shoot which is very short on the third level, but lengthens rapidly going down. These orebodies are practically homogeneous: they do not show the result of more than one period of vein formation. This means that the joining veins were contemporaneous, and that the field at and near the junction, where the differing solutions from the two veins mingled, was the site of unusually great precipitation. A number of other mineralogical features confirm this conclusion. For example, on the San Albino vein, little or no fluorite was noted for a hundred feet or so away from the junction; but beyond this the fluorite characteristic of this vein became plentiful. Again, the main or Coyote vein contains twice or thrice as much zinc as lead, except in that portion which is within the general field of the San Albino and Rica veins, where the ore contains only slightly more zinc than lead. Thus, each type of mineralizing solution has mingled with the other, not only at the junction, but for some distance away from it—producing an increased amount of quartz along the San Albino near the Coyote junction, and an increased amount of lead along the Coyote near the San Albino junction. Both classes of veins have been mainly deposited in open fissures, as shown by their sharp walls and their characteristic fine banding. We cannot, of course, believe that these long, deep, and wide fissures in shales (the veins are on the average many feet wide) existed prior

to the arrival of the ore-magma solutions; the fissures must have been forced apart by these solutions and so kept till consolidation was complete; and the fine banding I assume to be similar to that I have described as locally occurring in the Montana Tonopah mine and to represent that rhythmic precipitation from the ore magma, filling the fissure, which is characteristic of certain quartzose veins which have consolidated at the shallow and intermediate

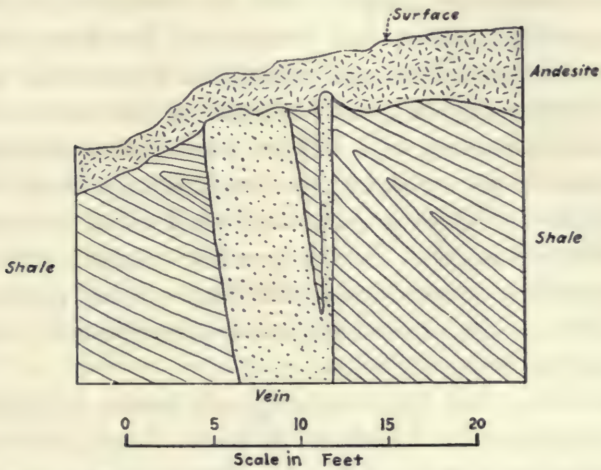


FIG. 112.—Cross-section of Cuadras vein, seven miles northwest of Santa Barbara, Chihuahua, Mexico. Ore-bearing banded quartz vein occupies slight fault fissure in highly folded Mesozoic shales, as shown by displacement of overturned fold. After erosion, outcrop of vein was covered by andesite flow. Note protuberance of quartz outcrops on original surface. After G. H. Garrey, field notes.

depths. The shale walls usually show relatively little disturbance. A section of a vein (Fig. 112) some six or eight miles from here shows the vein zone as a probable slight fault zone, judging from the correspondence in the folding of the shales on each side.

The ore on the Tecolotes vein outcrops at the surface; but the tops of the Coyote and San Albino oreshoots did not come to the surface. This is especially marked in the case of the San Albino, which offers a notable example of a weak vein at the surface strengthening decidedly in depth.

The proof here that ore-magma solutions of distinct type circulated along different fissures and mingled at junctions shows that *what appear to be branching veins are often really uniting veins.* Where there is a heavy deposition of ore at vein junctions this would appear to be always the case. In the instance of the Tecolotes vein, certain ore-magma solutions coming from the northeast welled up and southwest till they struck the northwest-trending main Coyote fissure and mingled with the distinct type of ore-magma solution filling that fissure. At Tecolotes, both ore magmas belonged to the general galena-blende zone, but the Coyote type, with its greater amount of zinc (about 10 per cent) and its average of 1 or 2 per cent copper, belongs to a somewhat deeper or higher temperature zone than the San Albino type, with its less zinc and copper and more highly argentiferous galena. This is another example of the fact that mingling of ore-magma solutions coming presumably from different foci of heat may cause precipitation diverging from the regular zonal rules.

There has been but one stage of fissure opening and fissure filling at the Tecolotes, as at the Eden, but the case I am about to describe differs in this respect.

At the Silver Lake mine, at Silverton, Colorado, I have observed a similar formation of oreshoots depending on similar junctions, and the same general types of solutions as at the Eden are shown. The values in these ores are in gold, silver, and copper, in which they differ from the Eden in having more silver. The veins are in Tertiary volcanic rocks of intermediate composition (latites, some andesites, locally rhyolites—some volcanic breccias) and occupy strong fracture zones, attended frequently by slight faulting; and evidence indicates that the ores were deposited in the last stages of volcanism, since a dike was noted which was later than the first stages of vein formation.

Since the period of fissuring coincided with that of invading mineral-bearing solutions, the openings became filled

and formed veins; and when such veins were split open by renewed movement along the fissures, they were cemented anew. These successive cementations are everywhere recognizable in studying the vein; and it is very interesting to note that they are not of the same material, but record a progressive change in the nature of the circulating solutions. Thus the different stages are to be considered as different or individual veins. As a rule the veins of the different stages were all formed along the same fissure, in measure as it was successively reopened: frequently, however, a vein or a certain portion of a vein was not reopened by the new period of stress, but during such a period fissures not before opened were created, though as a rule close to and frequently uniting with the old line of weakness. The sequence of vein deposition observed was: 1, Lead-silver ore: argentiferous silver and blende, with little gangue and little gold; 2, gold-copper-silver ore: quartz and cupriferous pyrite. These were the ore periods. Subsequently there were three distinct periods of barren gangue: 1, Mixed carbonates (of manganese, magnesium, iron, and probably lime); 2, quartz; 3, calcite. Some of these veins fault earlier veins; but usually they all occur together, making a compound vein. Thus the Richter vein, a simple vein of the barren quartz stage, faults the New York vein, which was, before faulting, a compound vein of the two metallic stages named above; and the quartz not only occupied the fault which displaced the sulphide vein, but followed and cemented new fissures following the old vein. The reopenings persisted after all vein-filling action was dead, resulting in shear zones, bands of gouge, and new water-courses.

I believe it worth while to go out of my way to point out the practical bearing of this vein history on mining. The events outlined may seem complicated, but their application to mining is simple; namely, that in following a vein, only material of the metallic stages should be followed, and the different stages of barren-gangue veins and barren

slip-fissures should not be followed far, under the false impression that the ore-bearing vein is being explored.

The vein fissures of the Silver Lake veins are of the successively branching type, much like those of the Eden, and the angle of junction is about the same. Orebodies have mainly originated near to and in consequence of the junction of branches; or, occasionally, near the intersection of crosscutting veins. The former is by far the commoner; the exact point of junction is not necessarily most highly mineralized, but the maximum ore deposition may extend along one or both of the joining branches from a point near the junction to a greater or less distance away from it; or may extend from near the junction along the united vein; or the result may be a combination of the two habits mentioned. Such oreshoots originated at the period of the metallic sulphide stages; the barren vein deposits of succeeding stages only served to break up the orebodies and to complicate exploring and mining.

In both these cases—that of the Eden and that of the Silver Lake mine—it is easy to recognize the normal magmatic stages of ore deposition—the lead-zinc (silver) stage and the normally higher-temperature-deposited copper (gold) stage; at the Eden differing solutions met and brought about the precipitation of both probably somewhat before their time, especially in the case of the lead-zinc solutions; and at Silver Lake, while the copper stage seems in part later, there was certainly a time and place of mingling of the two types of solutions (an overlap), and the maximum sulphide deposition, forming the oreshoots, was due to differing magmatic ore solutions advancing from different fractures and meeting at the confluence.

At the Aspen mine, in Silverton, a mile or two from the Silver Lake mines, I found[18] again the same type of compound veins due to repeated reopenings of the same type of fissure, and repeated refillings; and also the same sequence of metallic sulphide deposition. The succession was: 1, Argen-

[18] In 1907.

tiferous galena and blende, with practically no gangue and little gold; 2, gold-copper-silver ore (quartz and cupriferous pyrite). This corresponds exactly with the ore periods in the Silver Lake mine. As at the Silver Lake, the ore periods were succeeded by a series of barren-gangue or earthy-mineral veins, the Aspen succession being: 1, Quartz; 2, calcite and fluorite. The mixed carbonate veins which preceded the barren quartz in the Silver Lake mine were not noted in the Aspen mine.

The ores of the first stage have a lining or "casing" of quartz, usually comb-quartz, which separates the massive coarse galena-blende filling from the rock walls. While the sulphide may be several feet wide, the quartz casing runs from a fraction of an inch to several inches wide. This is a feature that I have frequently noted in massive galena-blende veins, as at Georgetown (Fig. 113). In noting the common occurrence of this comb-quartz casing I was somewhat at a loss to explain it, but the occurrence here at the Aspen mine makes its significance clearer: for here the quartz, which in Georgetown is quite free from sulphides, contains pyrite and cupriferous pyrite. Indeed, it closely resembles the abundant second stage of fissure filling by quartz carrying cupriferous pyrite (gold-copper-silver ore) listed above, and which I have interpreted as deposited at a higher temperature than the earlier galena-blende vein filling. The meaning of the quartz casing is in my opinion made quite clear by this circumstance. The fissures were filled, by injection, with a highly concentrated galena-blende magma, as I have argued for Georgetown (p. 137). The first precipitation was of quartz crystals, deposited before the cooling had progressed to the stage necessary for the crystallization of galena and blende: they started crystallizing on the walls, and grew freely out into the unconsolidated galena-blende magma (not into an open fissure). There was but little quartz present in the magma, however, so that it is represented only as a lining of the veins (except for the small veins or veinlets, where the

quartz casing constitutes the whole filling); and subsequently the galena-blende crystallized.

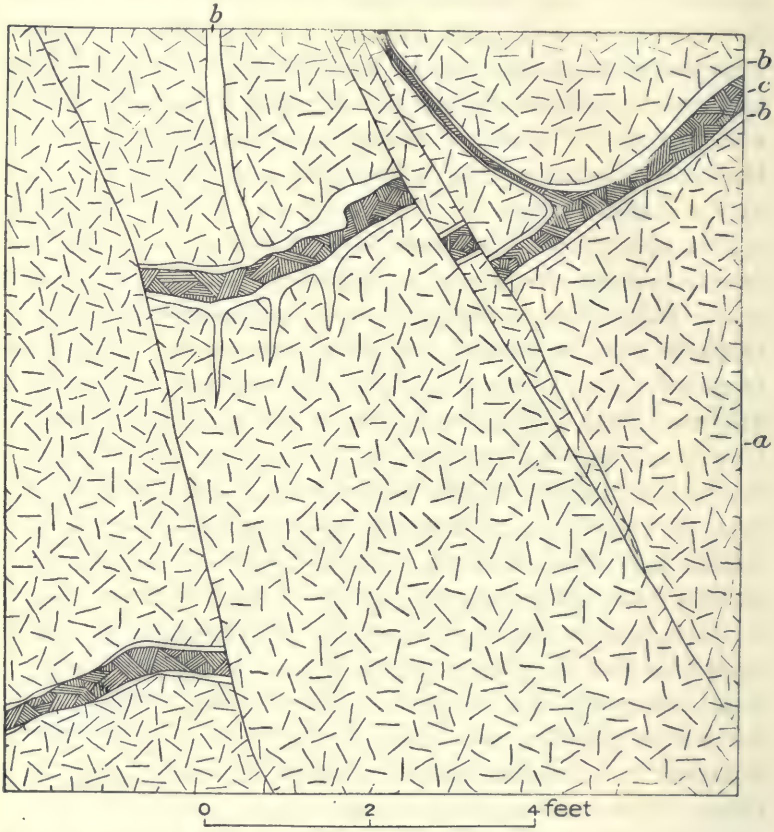


FIG. 113.—Georgetown, Colorado. Mendota vein. *a*, Granite, country rock; *b*, comb quartz without sulphides; *c*, sulphides without gangue (chiefly blende, a little galena, pyrite, and chalcopyrite). The vein has been faulted, but I do not wish to dwell on this. I wish to point out the "casing" (quartz, in this instance) and the subsequent filling of metallic sulphides. Where the fissure was narrow, the "casing" period filled it entirely. Where the fissure was wide, it formed only wall bands. The data exhibited show, to my mind, a single standing solution, distending the fissures, from which first quartz, and then sulphides, were deposited. After Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 66.

Another case of enrichment at junctions of two different types of veins, but representing different vein stages from

the examples above mentioned, is exhibited in the Pony Express mine, at Ouray, Colorado, which I examined in 1909. The district lies on the edge of the San Juan Mountains, where several thousand feet of Carboniferous and Mesozoic sedimentary rocks are exposed in canyon-like valley walls, and are overlain by thick Tertiary volcanics. Later than these volcanics are intrusive dikes and sheets of porphyry, soon after whose arrival fissure zones were formed and slight faulting took place; and soon after this the ore solutions had their brief stage in the play in this little theater, where a fragment of the world's history was enacted. There are three separate stages exhibited in the compound Bachelor vein. The first stage was a "spar" vein or veindike, consisting of barite, mixed earthy carbonates (of manganese, magnesia, iron, and lime) and some quartz containing disseminated sulphides and sulphantimonides, rich in silver. The second stage, strange to say, was a mud veindike (called by the miners, fairly enough, a "dike"), formed like the other stages, by ascending solutions (Fig. 158). The third stage was of blende, pyrite, and galena low in silver; and finally came a reopening later than the brief composite stage of ore formation, but these last openings were never to be traversed by ore-magma solutions and are uncemented. Now, the Bachelor vein is a good, straight, strong fissure vein, vertical and opened up for over a mile. But it splits or branches at one point. The branch makes an angle with the main vein of hardly more than 5° on the average, but the two, once parted, never again unite (Fig. 156, Chapter XIX). The linear continuation of the Bachelor vein they have called the Neodesha vein; the branch, the Pony Express. These two branches differ in their vein filling: as you may have guessed, the successive fillings which lay side by side so peaceably to form the compound Bachelor vein resolved themselves into two distinct and diverging veins at the split. The Neodesha vein was the spar and silver sulphide vein and was worked a long distance past the split, profitably. The Pony Express, however, was

the galena-blende-pyrite vein, and being low in silver, and the mass amount of galena and blende being relatively unimportant, it was not found profitable for more than a hundred feet beyond the junction, though it was drifted on for several hundred feet.

This occurrence is interesting and "somewhat different." It is interesting on various grounds, which I will note in passing. Take note of the two clean-cut stages of spar and rich silver sulphide ore and of galena-blende ore, separated by the unusual magmatic episode of the mud dike which came up under pressure. These metallic stages are the normal magmatic ones, representing the blende-galena zone and the normally overlying or later rich silver sulphide zone, whereas at the Eden and at Silver Lake (which latter lies also, like the Pony Express, in the San Juan region) we have the gold-copper zone and the normally overlying or later blende-galena zone. But the silver zone and the zinc-lead zones at the Pony Express have their normal order of age reversed, in which peculiarity they are identical with the occurrence at Aspen, where the same relation of the same stages occurs (p. 288). The normal order of the gold-copper zone and the blende-galena zone was also reversed in the Silver Lake mine. Apparently this inversion is a not uncommon one in the superficial volcanic rocks (and in the middle depths), and indicates a rising temperature during the critical post-intrusion period of ore deposition. Thus, both at Aspen and at the Pony Express the requisite temperature for the silver stage was raised to that necessary for the blende-galena stage; then dropped, as one might say from the results, almost perpendicularly. The ore-magmatic bolt was shot. Also at Silver Lake the initial ore-deposition temperature of the blende-galena stage was boosted to that of the gold-copper stage; but then dropped very suddenly and steeply, to the temperature of the barren-gangue stages.

Another point in all these instances is the renewed demonstration that the stages, probable temperature, and nature of ore deposition in the shallow-formed Tertiary

veins is the same as that normal to the deep-seated veins, and follows the same rule; and this is easier to see in the cases cited than in some others, where the stages are "telescoped" (Chapter VI), and the solutions have accordingly failed in the opportunity to differentiate according to temperature.

Reverting, however, to my main theme in this chapter, that of the precipitation of ore at the junction of branches, there was, as I understand it, no special enrichment at the junction of the Neodesha and the Pony Express veins; and thus the fact is shown that junctions of vein branches do not usually create enrichment, unless they bring about the mingling of different magmatic solutions. In this case there is a decided difference in age between the two types of veins in the two branches; and so we can understand why the two types of solutions did not overlap in time of arrival and so did not at any stage mingle and produce unusual precipitation.

While we are on the subject of magmatic stages in the Tertiary gold-silver veins, and while we are in the San Juan, I am going to mention the Camp Bird mine, several miles from the Pony Express, and at a much higher geologic horizon—entirely in the volcanic flows which cap the sedimentaries in which the Pony Express lies. The Camp Bird vein (Fig. 114) is in andesite—a succession of flows and breccias. It is, like the Bachelor vein, a fine, clear type of a compound vein, but the stages are not the same. I have examined and mapped this mine. The first stage was a considerable fissure-vein filling of slightly argentiferous galena, zinc-blende, and pyrite which is often slightly cupriferous. Rhodonite was formed, chiefly by alteration of the wall rocks. We have, of course, no difficulty in recognizing this magmatic stage, any more than we have at the Eden, the Silver Lake, or the Pony Express—the blende-galena stage, reaching up in its range enough so that the galena is argentiferous, down enough so as to touch slightly the copper—a little wider bracketing or telescoping, there-

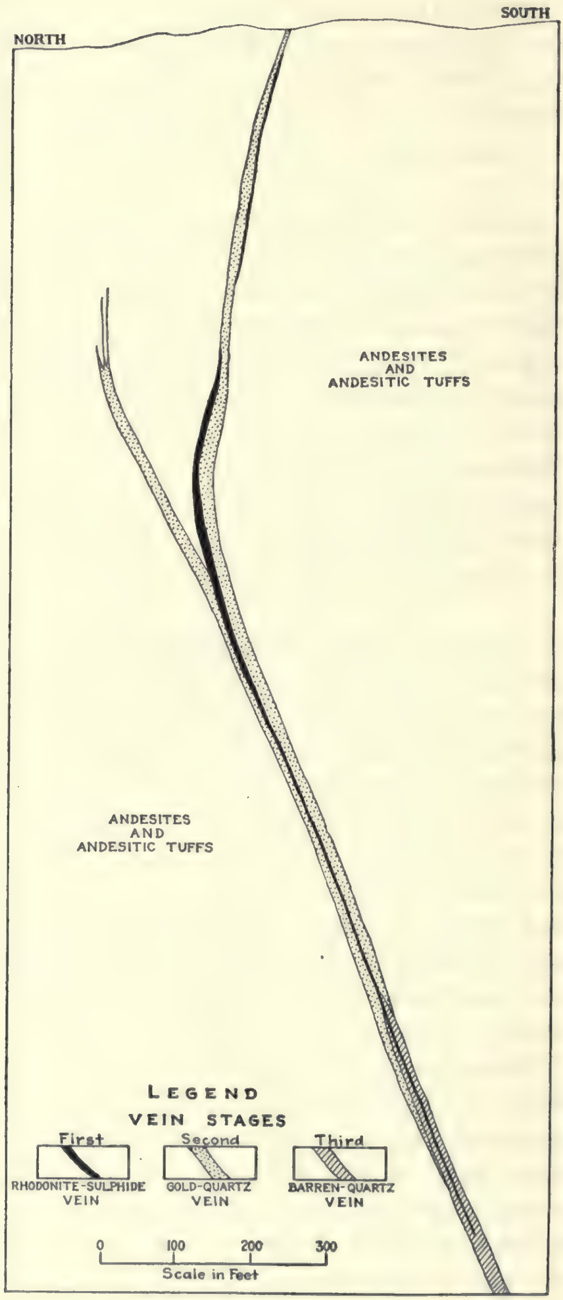


Fig. 114—Cross-section of Camp Bird vein, Ouray, Colorado; from surface to fourth level. A study of a compound vein. Rocks are horizontally bedded andesites and andesitic tuffs. Note: The second stage—gold-quartz—came in again in this section below the fourth level, but it is impracticable to show a section of such length. By J. E. Spurr.

fore, than in the corresponding stage at the other San Juan mines which I have described. This lead-silver ore was what the Camp Bird mine was first opened up and mined for; and simple veins of this stage and no other occur close by. But the Camp Bird fissure was subsequently reopened by the pressure of a new type of invading ore-magma solution, and this deposited, along the side of the old vein, and to a less extent in new parallel fissures, quartz—practically just plain quartz, but carrying much free gold. This quartz was put over the dump as waste when the mine was being worked for its lead and silver; but a chance assay made a mine and a millionaire—Tom Walsh. The new gold-quartz vein carries a very little sulphide of lead, zinc, and iron; it has dissolved some of the old sulphide vein, where it comes in contact with it, and reprecipitated, in little nooks, some of the sulphides and rhodonite along with the quartz. Finally, and entirely subsequently, there was a cavernous, vuggy, comby quartz, quite barren. We may disregard it: it teaches us only one lesson that I know of—namely, the difference between the certainly aqueous solution—we may as well call it water—which is indicated here as the last vein-forming agency, and the solutions which formed the first two (metalliferous) stages, which have infilled bodies or veindikes showing neither comb quartz nor vugs, but of massive texture, indicating no gradual deposition from walls to center, but an injection of ore magmas (with a minimum, apparently, of water and some other gaseous material—there is a little fluorite), which crystallized after intrusion. After the barren quartz (magmatic-water-deposited) vein, there were formed fissures which are still unoccupied. As to the gold-quartz vein—evidently a magmatic stage of ore solution: what stage which we know in the plutonic ores does it represent? Does it correspond to the relatively high-temperature gold-quartz veins which normally underlie the (silver) lead-zinc-(copper) zone exhibited by the first Camp Bird vein, and is it the same stage as the gold-quartz veins in California,

Ontario, and Australia, but representing the shallow-formed "volcanic" type, while those last named represent the "plutonic" type? Or does it represent a special type, not paralleled by plutonic veins—a sort of distillation from a high-temperature ore magma close to the surface, by which the distilled gold is added to a normally barren quartz magma, which otherwise would have solidified as a quartz vein of the barren-gangue stage? On this difficult problem see the discussion in the latter part of this chapter. The rich Camp Bird ores occupy a definite restricted vertical zone, elongated horizontally, with a definite top or "crest," parallel to the surface above, where there is nowhere an indication of a rich vein.

But reverting again to our theme of the precipitation by the mingling of magmatic solutions, at junctions: both the old (lead-zinc) and the new (gold-quartz) Camp Bird veins branch; but there is no especial enrichment at or near the intersections. The stages of the two veins were quite distinct. Therefore, the two types of ore magma, as at the Pony Express, never mingled; hence the lack of enrichment at junctions or intersections. The Camp Bird vein in its course (N. 70° W.) intersects a number of simple (not compound) lead-silver veins, like the old Camp Bird filling. These veins run mostly N. 45° W. There is no enrichment at the intersections.

In Tonopah[19] (Fig. 115) the veins are of the splitting, branching, and sometimes reuniting type, but there is no enrichment at intersections, no enrichment at junctions. The Tonopah veins show diverse successive stages, but the veins shown in the figure (the first-period veins) represented a single injection, and were separated from the next stage of ore-magma injection by a distinct time interval marked by a barren andesite intrusion.[20]

I suspect, therefore, that we can lay down some tentative but probably sound principles regarding the frequently

[19] *Professional Paper* 42, U. S. Geol. Surv., p. 84.

[20] J. E. Spurr: *Econ. Geol.*, Vol. X, No. 8, Dec., 1915, p. 765.

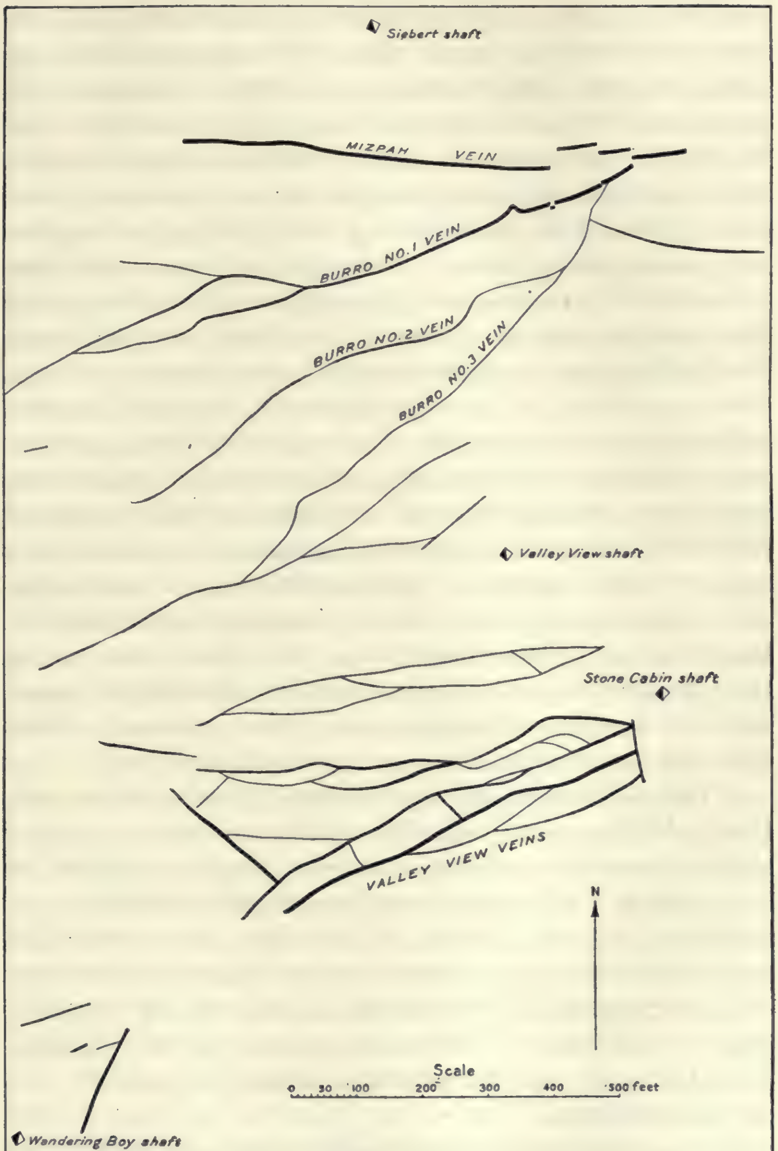


FIG. 115.—Outcropping veins at Tonopah, Nevada. Examples of the branching, "linked" type of fissures, formed close to the surface. After J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Plate XVII.

observed formation of oreshoots or enrichments at junctions of branching veins: that where present they are mainly due to the commingling of diverse magmatic ore solutions. I do not believe that they can be ascribed to the meeting of a magma ore solution with circulating ground waters or even hot-spring waters, as we understand these terms: this would probably tend to dilute the ore magmas and prevent precipitation. Moreover, we can conclude that there will be no enrichment (of the type which extends from the junction along the prongs of the fork, and back along the handle) where the stages of ore-magma solutions, though diverse, are found to have been distinctly separated in point of time as to their arrival; but only when they are contemporaneous or overlapping and hence can at some stage meet from different fissures. Exceptions will be noted to this rule, in the case of intersecting fissures, where a later vein is locally assisted in its precipitation by meeting an older sulphide vein, for at such a junction a certain enrichment may sometimes take place; but this is not due to the mingling of fluid solutions and is identical in nature with the accelerated precipitation of a vein where it intersects a basic, sulphide-bearing, or carbonaceous rock.

A slight difference in the character of ore-magma solutions which are in a transitional stage, involving even a slight alteration of chemical content, may be sufficient to bring about a somewhat more intensified precipitation of metals at or near junctions of branches, even where it is not very evident that more than a single stage of ore-solution magma is represented in the vein or veindike. And it is always best, therefore, in each district, by geological surveys and comparative assays, to ascertain the actual conditions.

Let me instance the remarkably interesting gold-quartz veins at Aurora, Nevada, which I have studied very carefully. These veins are in Tertiary andesite. Slightly later than the veins, but only slightly, so as to be contemporaneous with the last stages of silica injection, is rhyolite,

in dikes and great overwhelming flows. Still later, after erosion had exposed the veins, came flows of Pleistocene olivine basalt, referable to a recent crater which stands a few miles away, and whose products cover the extensions of the exposed mineral district. The veins are entirely of quartz, and are remarkably wide, regular, and persistent bodies, ranging in width up to 40, 50, or even 100 feet, sometimes extending at least a mile or two along the strike, and usually steeply dipping or even vertical. They strike N. 60° E., thus observing the rule of the easterly-westerly strike of mineral veins in the Cordilleran region of North America.[21]

The quartz has clean, sharp contacts with the wall-rock andesite, which is relatively fresh—except very close to the contact, where the biotites are bleached and there is a little silicification. The same sharp contacts and relatively slight alterations are true of angular fragments which occur, unsupported, in the quartz. There are no sulphides in the quartz, which is white and frosty, looking usually much like a broken surface of stone china. The values are probably in fine native gold, but are so disseminated as to be revealed only by the assay, which is in general the only way to distinguish between the very low-grade and the better-grade portions of the vein; the silver values (for the ore carries some silver) are very likely partly in sulphides, like argentite, but so finely disseminated, if this is the case, that only the faint bluish nature of some of the quartz betrays it. I have made no microscopic study. Ordinary sulphides, like galena and blende, are absolutely wanting.[22]

Clearly, these gold-quartz veins are veindikes; I may go further and call them gold-quartz dikes, for the lack of alteration of wall rocks and the included angular fragments shows the lack of any appreciable amount of surplus aque-

[21] Chapter X, p. 479.

[22] This statement is not intended to mean that a diligent search of the district might not reveal a few crystals of sulphides. I have seen some of pyrite, but none of galena, blende, or chalcopyrite; nor are there any copper or even iron stainings, as a rule, in the veins.

ous or gaseous components, such as would have been expelled on the consolidation of an aqueous quartz magma. No essential part of the quartz is due to replacement; it is a fissure filling; and the maintenance of great widths by the veindikes, and the inclusion of angular fragments of the wall rock which have not sunk in the quartz magma, show that gaseous tension of the magma enabled it to be intrusive and create its own fissure, quite like a dike of rhyolite, and the quartz magma was viscous enough *or under enough upward current* to support the certainly heavier andesite inclusions.[23] In other words, this was a relatively dry or aplitic quartz magma.[24] Actually, it is our old friend, the intrusive quartz dike or veindike, possibly a little dryer and a little simpler in composition than usual.

This district throws a great light on the intimate relations of gold-quartz Tertiary veins and silver-quartz Tertiary veins. As has long been known, in different districts such veins carry gold and silver in all proportions, from practi-

[23] I think I should summarize briefly my conclusions as to the occurrence of unsupported angular fragments in mineral veindikes. Where the fragments are of light material, it is likely in some cases that the fluid ore-magma solution had a greater specific gravity, which would account for the suspension of the fragments. But there are frequent cases where the inclosing vein material, as in the instances above, is, even after consolidation, lighter than the inclosed blocks and fragments, just as is often the case with igneous rocks (like rhyolite) and their inclusions. Viscosity of an injected vein solution and sudden congelation thereafter will explain some cases of suspended fragments heavier than the inclosing vein matrix. But where a vein having a banded structure, indicating more gradual consolidation, incloses such supported fragments (as is sometimes the case) we must look for still another explanation, for differences in gravity operate in time, even in a viscous fluid. A cork will work its way upward through a barrel of tar, it is said. Some force must have offset gravity, tending to push the fragments up, as gravity tended to pull them down, with the result that they were caught balanced or suspended when the vein solution in which they were swimming froze to form the vein. I suggest that gaseous-tension pressure may have been this gravity-antagonizing course, theorizing that the relief of this tension must have been upward more than downward at the stage in question; or possibly an upward flowage current of the vein magma may in part account for the phenomena.

[24] Chapter VII, p. 316.

cally all silver and no gold, as at Pachuca and Guanajuato, to practically all gold, as at Goldfield. Goldfield, Tonopah, Divide, and Aurora all occur in the same general region of Tertiary mineralization. At Tonopah both gold and silver are present in the proportion of about 1 to 100 by weight.[25] At Divide, four miles away, the principal mine has ore containing gold and silver in the proportion of 1 to 200,[26] but there are other Tertiary gold-quartz veins of the same general period at Divide in which the values are nearly all gold. At Aurora, in veins which seem to be all of the same nature and age, the proportion of gold and silver varies from 1 to 2 or 3 by weight (as in the Humboldt vein) to 1 to 35 to 46 in the Old Esmeralda—both great wide quartz veins of the same type, in andesite. In the Juanita claim, of two veins lying side by side, and of identical appearance, one carries gold to silver equal to 1 to 7.6 by weight, and the other 1 to 2.6. In the Prospectus vein, the lowest-grade, or third-class, ore shows the proportion 1 to 7.3; the second-class 1 to 3.4; and the first-class or highest-grade, 1 to 1. Exhaustive sampling of these properties enables me to speak accurately. This illustrates how delicate were the conditions that determined the relative concentration of gold and silver in different portions in a common siliceous ore magma; and the close relation of districts of this Tertiary type which differ in their gold-silver ratio may be understood from this composite example.

However, I am able, I think, to elucidate the problem still further from my studies at Aurora, for there are various bits of evidence that the silver was most abundant in the earlier veindike stage of consolidation, the gold in the later. In one end of the district veins containing gold to silver in the ratio of 1 to 2.1 were found to cut others having a ratio of 1 to 4.3.

My detailed description of the quartz of these Aurora

[25] J. E. Spurr: *Professional Paper* 42, U. S. Geol. Surv., p. 8.
[26] A. Knopf: Bulletin 715-K, U. S. Geol. Surv., 1921, p. 148.

veins, taken from my field notes made in 1910, is, I think, worth recording:

"The veins consist of fine granular quartz, the coarsest of which is like that of the first-period veins at Tonopah, but the commonest phase is finer and frosty-lustered, resembling the second-period West End vein of Tonopah. From this most common type, the quartz increases locally in fineness, some bands having a porcelainic texture, and alternating with the frosty type. Such bandings, often beautiful to see, also form concentric rings about fragments of andesite inclosed in the vein." Please do not infer from the above description that there is any evidence of progressive fissure filling in these veins. There is none; the quartz is homogeneous from wall to wall. The phenomena are those of a crystallizing magma and are those of a pulsating crystallization, such as I have discussed for veins, as in some instances at Tonopah; and which sometimes occurs also in diorites and in granites.

Reverting again to our main thread of thought, on which I have strung, like beads, these successive illustrations of different districts, with sidelights as to their concomitant characteristics: we find at Aurora, a distinct though slight tendency, in some parts of certain veins especially—the general vicinity of certain vein junctions—toward a greater precipitation of primary gold in the quartz (as indicated by comparative assays) than ordinarily is the case, thus forming oreshoots. Although the quartz magma at Aurora was auriferous throughout—out of thousands of assays of all kinds of quartz, I do not recall ever having had a blank, although the low-grade ore will often run much less than a dollar a ton in value—only in certain veins and certain parts of veins is there gold enough to have tempted mining. The big veins are not workable except for these "shoots." Therefore, we must assume some slight modification of conditions in these vein fissures in some places, arising from the meeting of the ore magmas at some junctions; and this modification we may believe to be due to the

confluence of very slightly different stages, which are indicated by the observed transition between the earlier more argentiferous quartz and the later more auriferous quartz.

This is one of the factors forming these oreshoots (which are not very strongly marked at the best); but the description would not be complete did I not discuss another patent factor. Be it understood that in this district (in which it is not peculiar), some (but only some) of the narrow veins are relatively high grade (say $10) throughout, while others are low grade (say $1 to $2 or less) throughout; however, the big veins are never all pay-ore, but are very low grade except for local concentrations or shoots similar in nature and grade to the better class of narrow veins. Such a pay-streak in the big veins generally runs along one wall, or both walls, and may or may not be in the evidently favorable field of a junction of branches. Exceptionally, however, it may run in the middle of a big low-grade vein, as in the case of the Prospectus vein (Fig. 116) and other big veins at Aurora. Although in general no lines of contact can be observed between the high-grade streaks and the low-grade quartz, it is believed from the above relations that the higher-grade quartz is the younger; yet from the frequent lack of clear definition it must be nevertheless well within the general crystallizing period of the veindike, which, moreover, crystallized in one stage. In other words, the richer gold-quartz must be considered in the nature of a magmatic differentiation in the veindike.

Let us inquire, so far as we can, how this differentiation of richer streaks comes about. A selected specimen of rare rich quartz from one of the veins is bluish, and in this case (which is probably exceptional) distinctly cuts older quartz. The contact against the older quartz is marked by an especially dark streak, which is the richest, running around $100 per ton. I have collected a very similar specimen from the Valley View vein, in Tonopah, where new quartz forms fissures in old quartz, and has rich black precipitation rims against the old quartz. These rich precipitation rims of

veins and veinlets, against the walls, are common. I have previously ascribed them to physicochemical reaction between the vein solutions and the wall rock; and at Tonopah

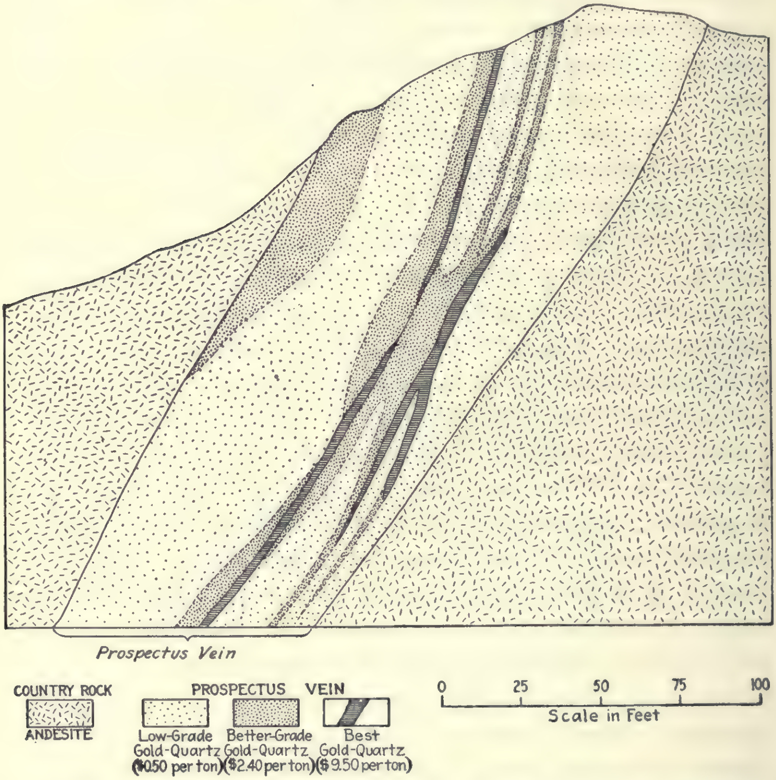


FIG. 116.—Cross-section of Prospectus vein, Aurora, Nevada, developed by mine workings; surveyed and assayed by J. E. Spurr and staff. A "true fissure vein" in spite of the great width, with sharp, clean walls; has not originated by replacement. This is not a compound vein, but a one-stage vein; the relative concentration of gold shown in the quartz was accomplished before or during the crystallization of the quartz, and belongs to the phenomena of "magmatic differentiation."

believed that the andesitic wall rock thus had a screening effect, which retarded and precipitated the metallic sulphides, but admitted the silica and potash—but soon precipitated these also, leaving only principally the gaseous components of the vein solutions, like carbon dioxide and

sulphurous gases, to travel further on, and alter the rock. But what shall we say when we find this precipitation rim of quartz against quartz? No purely chemical reaction can have taken place; nor is the quartz wall absorbent, so that it could have served as a physicochemical screen. In the Aurora rich ore specimen above referred to the width of the black precipitation rim is invariable (about 1/12 inch), although the width of the whole later (richer) quartz vein which it borders varies from 2 inches to a mere crack. Therefore, where the veinlet is under about 1/6 inch in width it is entirely composed of this precipitate. Moreover, where fragments of the older quartz appear in this younger quartz veinlet, they are rimmed by the precipitation zone, of the same (1/12 inch) thickness; and this observation extends down to quartz fragments at least as small as 1/10 inch in diameter: where, locally, therefore, the whole vein is full of close-packed small inclusions of the older low-grade quartz, and is an inch wide, the entire cementing material is this black precipitate. These observations show clearly that the amount of precipitation is neither dependent on the width of the vein nor on the mass of the included fragments or wall rocks; but is directly dependent upon the surface area of the older quartz. It is further improbable that the temperature of these included fragments differed from that of the solution, for if such were the case the large fragments and the walls would have been cooler than the small fragments, and would show stronger and longer precipitation.

Therefore, as to the power which enabled the gold to travel through the siliceous magma to its margins, there to be precipitated, I suggest the action of differential gaseous tension, the metallic elements having, as I assume, a higher gaseous tension than the silica. This would explain the precipitative rim of equal width, whatever the width of the veinlet: it would also explain, in the wide quartz veins, which run from a score to several score feet in width, why

the richer ore is so often found along one[27] or both walls. It would further explain why small and narrow veins, on the periphery of the big quartz masses, but connecting with them, may be rendered high grade, and why so many high-grade stringers and narrow veins accompany large, low-grade veins; and, conversely, why so many large quartz veins are apt to be, on the whole, of low grade. I am not discarding, in addition, the theory of the physico-chemical screening operation of the vein wall rock in certain cases: but I do not think it has been operative at Aurora, where its lack enables us to perceive the true magmatic

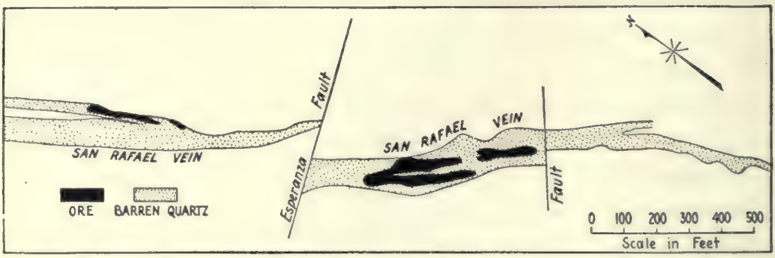


FIG. 117.—Esperanza mine, El Oro, Mexico. Plan of San Rafael vein, on fourth level, showing characteristic localization of ore in barren quartz vein.

differentiation process which must be one of the important processes resulting in higher-grade ores. When the consolidating quartz magma produces an incipient rift or line of relief of tension in the center of the vein, then the metallic sulphides, driven through the siliceous magma by gaseous tension, may seek this central rift in preference to the walls, as in the case of the Prospectus vein (Fig. 116), and the richer oreshoot will have been formed accordingly.

The segregation of the metals into the *interior* of a great quartz vein, instead of along the margins, is well shown by the San Rafael vein, at El Oro, Mexico, which I shall presently refer to in another connection (Fig. 117).

It will be seen that this principle is the same as that which I have appealed to as having determined in many

[27] Especially the hanging wall.

cases the deposits of metallic sulphides on igneous contacts, whether siliceous or basic; and to which I have also appealed for rock-magma differentiation in general, as illustrated in the Ural dunite-pyroxenite-gabbro-granite differentiation; and that in all these cases it is something more than fractional crystallization. This probably has its part, but also the differentiation process is certainly operative in magmas (rock or vein) in which the congelation is only incipient.

The phenomenon of differentiation of the rich ore usually to the margins of wide quartz veins, but less frequently

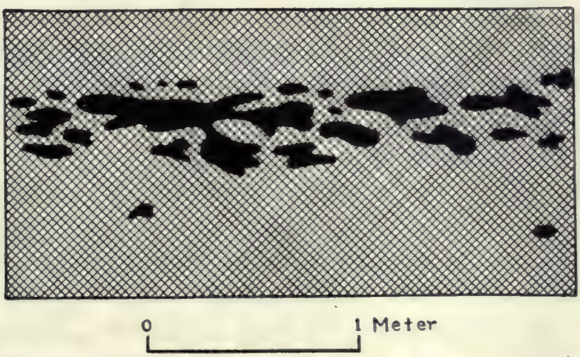


FIG. 118.—Magmatic segregations of chromite in peridotite. Hestmandö, Norway. After J. H. L. Vogt: Zeit. f. prakt. Geol.; 1894, p. 391.

to their center, is analogous to the differentiation in dikes, whereby the margins sometimes become more siliceous than the center, while in other cases the more siliceous portion is segregated in the center (Chapter XII, p. 578). It is even more strikingly analogous to the differentiation of ores from basic magmas, where the ores ordinarily are propelled to the margin of the intrusion (Fig. 93), but not infrequently to some interior station, along an indicated line of incipient fissuring or release of tension (Fig. 118).

In many vein sequences in mining districts which I have described, the latest of the magmatic vein stages has been calcite, which occurs characteristically in wide fissure veins.

This is the case, among the deeper ores, at Matehuala and at Velardeña,[28] for example. Among the Tertiary veins mentioned in this chapter I have recorded the same for Silver Lake. Such veins are very common as the last stage: they are magmatic, for subsequent fissuring is uncemented, although in many cases old. In all these instances and many others, these calcite veins are the latest stage of the "zone of barren-gangue veins," as I have called them, which are later than the metalliferous veins. If, however, the normal order of vertical succession due to decreasing temperature upward away from the focus of ore deposition be reversed, and the temperature should rise subsequent to the formation of these calcite veins, then the metal-bearing siliceous ore-magma solutions will have their natural precipitation zone where before was the zone of calcite deposition. Thus, where an older calcite vein is split open, and a siliceous vein magma fills the fissure, it is natural that the siliceous solution magma will replace the calcite, instead of just splitting it and lying alongside of it. And we find this, indeed, a very common phenomenon in the Tertiary shallow-formed veins.

Such, for example, is the case at El Oro, Mexico, and between El Oro and the Dos Estrellas mines, where I have observed different veins showing all stages between calcite veins and a complete replacement of the calcite by quartz. The calcite is barren; but the quartz is gold bearing, or both gold and silver bearing. The different proportions of gold and silver in the ore (which in places, as in the famous West vein of the Esperanza mine, is very rich) are as variable as at Aurora. The ore carries free gold and rich primary silver sulphides, like argentite, stephanite, etc., with a very little zinc, but no lead or copper. In the San Rafael and associated veins, the general proportion of gold to silver by weight is 1 to 6. In similar veins which are of prime importance in the same district the proportion varies—in the Dos Estrellas the proportion of silver is considerably

[28] See pp. 259 and 269.

higher, while in the Borda bonanza the values were chiefly in silver. In the San Rafael vein, moreover, extraction of the ore showed that the average values on the upper levels were: gold to silver, by weight, 1 to 3; while on the seventh level the average values were 1 to 6. The richest veins are among those showing most complete replacement of calcite by quartz, this change being evidenced by pseudomorphs, or crystalline calcite changed to quartz. Yet there was seen in parts of the same veins, a later crystalline calcite period, the calcite occurring in fissure veins, which replaced the quartz,[29] which had itself on a large scale replaced the earlier calcite, which on as large a scale had formed the first veins of the district. All these veins are in andesite and slate. Here, then, in the El Oro district, is a clear evidence of the reversal of the order of vein formation by a raising of the temperature during the process, so that the zone of gold-silver quartz vein formation rose up to the barren calcite veins and partly replaced them; after which a sinking of the temperature superimposed last of all the barren magmatic calcite zone again.

Such earlier barren calcite veins, replaced, to a greater or less degree, by gold- and silver-bearing quartz, or by gold-bearing quartz, I have observed in many other mining districts, such as Oaxaca, in Mexico, and a number of places in Nevada. Where the silicification has been partial, it may extend chiefly along the cleavages between the crystals; and if, as often may have happened, the vein has subsequently been leached by surface waters, the calcite may have been leached out, leaving the skeleton of quartz.

A still more striking result of partial silicification followed by dissolving out of the calcite is one which I have noted at several places in Nevada, especially at the Ideal prospect, not far from Mina, Nevada. Here the gold-bearing quartz had formed isolated crystals shot through the calcite vein by replacement, much after the fashion, apparently,

[29] At Matehuala, also, the calcite of this stage replaced earlier quartz. See Chapter V, p. 261.

of the partial silicification of limestone, as I have described it at Aspen (Fig. 91, p. 573); and subsequent dissolving out of the calcite near the surface has left an incoherent loose auriferous quartz sand (a perfect, though angular, sand, running like the sand of the seashore) between the vein walls, which only required shoveling. Unfortunately, I did not find it of high enough grade, or in large enough quantity, to warrant mining operations. Lower levels in this and similar mines which I investigated in Nevada show the calcite only partially leached from the firm vein-mass.

At Ball Mountain, near the now abandoned Nevada Wonder mine, at Wonder, I explored similar veins whose width was up to 50 or even 100 feet, which were about three-fourths crystalline calcite, replaced in grains, seams, streaks, and more solid veinlets by about 25 per cent or less of dense white or fine granular quartz, showing in part a structure pseudomorphic after the calcite. The calcite is barren: the quartz contains free gold and finely disseminated silver sulphides, the proportion of gold to silver in the ore being about 1 to 10 by weight. As the average of the better portions of these ores ran less than $3, no mining operations were feasible. I mention the large size and low values of this type of veins, of which I explored, developed, and sampled several, to show the low grade of mineralization brought about by only a partial replacement of the barren calcite veins by gold- and silver-bearing quartz.

The barren calcite veins of this Tertiary type are quite like the latest barren calcite veins which at Velardeña, Matehuala, and like districts were the last vein stage in a consecutive and closely allied series of magmatic deposits, of which the earliest were copper sulphides (chalcopyrite) with a gangue of lime silicates (the so commonly called contact-metamorphic deposits), and all formed as an after-product of monzonitic or dioritic intrusions into limestone; while the quartz veins correspond fairly well with the important veins of the Terneras type,[30] which are quartz veins

[30] J. E. Spurr: *Econ. Geol.,* Vol. III, No. 8, p. 715.

containing about one-half as much calcite as quartz and whose chief values are in gold and silver in the average proportion by weight of 1 to 240; or with the silver-bearing quartz veins of the Angangueo district (p. 272). Thus the silver-bearing quartz veins of this superficial Tertiary type, found replacing these calcite veins by virtue apparently of a rise in the temperature zone, seem to correspond with the uppermost metal-bearing zone determined in the deeply eroded districts mentioned—seem to represent, in the typical vein sequence as displayed under the favorable condition of leisurely vein formation in depth, the principal silver zone, which is the uppermost of the regular and typical metal zones, and directly underlies the zone of barren gangues. Therefore, it appears the normal thing that a rise in the temperature zones should cause an invasion of earlier-formed calcite veins by siliceous silver-bearing magma solutions.

Where, as is so frequently the case, however, gold occurs with this silver in various proportions, sometimes predominating, as in dozens of camps which will easily come to mind, then the presence of gold is not so easily understood, and is a most perplexing problem.

My present working hypothesis is that this gold is the result of the disintegration of a high-temperature ore magma by great lightening of pressure, very close to the surface. A clew to its origin may be contained in the presence of metallic gold around the orifices of certain hot springs, as at Steamboat Springs, in Nevada; another indication is very possibly contained in an ore deposit like that of Mercur, where gold occurs associated intimately with realgar and cinnabar, and without other close associates, and is a distinctly later formation than quartz veins carrying silver, which we may well suppose to represent the highest silver-bearing zone. Both stages at Mercur followed an igneous intrusion; but they certainly represent different processes, for while the silver veins have a very abundant quartz gangue, and so represent the siliceous ore

magma, the gold ores have no quartz or other gangue, and clearly represent the escapement, from the ore magma, of volatile metals like arsenic and mercury dissociated from the earthy components of the magma solution; and it is in such company that the gold occurs.

As I have shown, exactly the same orderly stages of metallic vein formation ordinarily take place in the Tertiary lavas (where opportunity offers), as at greater depths in association with dike rocks, or still deeper in association with granular ("plutonic") intrusives. This is seen not only in the San Juan country in Colorado, mentioned above, but, for example, in the Tertiary volcanic district of Inde, in Mexico,[31] in which the regular series of veins begins with those carrying copper and having a lime-silicate gangue and proceeds to arsenopyrite veins, lead and zinc veins, argentiferous quartz veins, and finally to barren veins in different stages—mixed earthy carbonates, barite, and calcite; all quite similar to the succession at Matehuala (p. 258) or Velardeña (p. 269)—to refer to types of vein sequences associated with granular intrusives. But in these usual sequences in and associated with Tertiary lavas, quite as in the case of the deeper-formed veins, the latest metalliferous vein formations are the silver veins, usually with quartz gangue, but sometimes with a gangue of barite; and after these there come only the veins of the barren gangue minerals.

In none of the instances where these sequences are displayed have I found a gold-quartz stage later than the silver-quartz stage; and the stage preceding the silver-quartz stage is invariably (where the succession is normal) the galena stage. Therefore, since the replacement of the calcite veins in the Tertiary lavas is due to a rise in temperature, why are not the silver-bearing quartz veins first superimposed upon the calcite veins, and next, not gold-quartz veins, but the "base-metal" veins, with their orderly natural sequence, of lead, zinc, and copper, before

[31] My own unpublished studies. See p. 804.

the zone of the normally deep-seated gold-quartz veins is reached? The fact that the calcite veins are replaced by quartz veins varying in content between predominating silver and predominating gold indicates some special phenomenon of gold deposition peculiar to very shallow depths, and only there exhibited, and forming a mixture in all proportions with that silver-bearing quartz which appears to be of the normal type and stage familiar in deeper-formed deposits.

Each of the observed rather completely represented vein stages in Tertiary lavas, which run from copper ores up the gamut to silver-quartz ores, and from there on to the invariable wide veins of barren calcite, which closes the usual magmatic series, of course represents, even though shallow-formed, a zone relatively deeper than a series of zones which we can picture as having been removed by erosion; for example, a slightly higher zone than that now occupied by copper-bearing veins will have contained no copper ores, but will have showed blende-galena veins; still closer to the surface these zinc-lead veins will not have been present, but the silver-quartz veins will have existed; and still higher, quite near the surface, no metalliferous veins will have been formed, but only the barren gangue veins, and, in nearly all cases, the wide, barren calcite veins. It is such a zone as the last that we actually have under consideration in connection with the problem in question, for these wide calcite veins which have been more or less replaced by quartz are not parts of a compounded sequence (as they occur in many districts), but are the only veins shown. They must have formed not very remote from the surface; and it is evident that their appearance would have been the end of the vein sequence if it had not been for a raising of the temperature, and a consequent moving upward of the respective zones of vein formation, which must bring these metalliferous zones very near the surface indeed. Does this unusual relief of pressure operate to release and dissociate the gold from the column of ore

magma in a way unknown even at moderately greater depths? There is some evidence that such is the case in the Mercur occurrence.

Suppose, now, that in the Mercur occurrence, the typical ore magma which formed the earlier silver-quartz vein had not consolidated, and the volatile emanations from below which deposited the gold, with realgar and cinnabar, but no gangue, had risen along different channels and mingled with the silver-silica gangue: would we not have a silver-gold-quartz magma by the mixture, and one in which the mixture would have been in all proportions? I have felt (p. 616) that the relatively high position of the rich silver zone, being the last or uppermost regular zone, was connected with the association with the silver of the volatile elements, arsenic and antimony, for the silver in this zone occurs in considerable part as sulpharsenides and sulphantimonides, whereas silver in a less concentrated form occurs in the galena zone, next below, where it is not characteristically associated with arsenic and antimony; and the levitancy of the gold in the case assumed above may be due to the release, under especially light pressure, of this metal as carried by easily volatile components of the magma. The frequent presence in the very superficial gold ores, of much tellurium, and even selenium, elements which are indeed found in the deep gold-quartz veins, but not in such abundance (just as the gold in these deep veins is characteristically not so richly concentrated as in many of the superficial vein occurrences), strengthens this suggestion that an escapement of these volatile elements, carrying with them the gold, takes place at a very reduced pressure, quite near the surface, from the characteristic ore magma which usually consolidates at considerable depths. Thus we may explain why, in veins like those of Tonopah, where the characteristic materials of some of the deeper vein zones are represented, the veins seem "sweetened" or enriched out of proportion, in gold and silver—that is, the gold and silver values dwarf by comparison the relatively small

amounts and small representation of the base metals. This may also explain why at Goldfield the very rich gold-quartz ores pass in depth to an ore carrying much copper, testifying in this way to a sort of differential distillation under very slight pressure but high temperature: slight pressure, because the conditions at Goldfield indicate that the rich ores were formed only a few hundred feet below the surface; and high temperature, as indicated by the copper ore. The gold ore contains the volatile metals arsenic, antimony, bismuth, selenium, and tellurium.

Altogether, I am led back to believe in the general correctness of my previous characterization of the superficial silver-gold zone, first made in 1907,[32] and to believe that it will be difficult for me to improve the general statement of the law of vein sequence as slightly revised in 1912[33]:

"A. The pegmatite zone, containing tin, molybdenum, tungsten, etc., with characteristic gangue minerals, such as tourmaline, topaz, muscovite, beryl, etc.

"B. The free gold-auriferous pyrite zone, with coarse quartz gangue. (Principal gold zone.)

"C. The cupriferous pyrite zone. (Principal copper zone.)

"D. The zone of argentiferous pyrite and auriferous arsenopyrite. Either one may be represented to the exclusion of the other, indicating a subdivision of this zone. Silver may fail in the pyrite and gold in the arsenopyrite. (Principal arsenic zone.) A frequent mineral of this zone is pyrrhotite. Antimony may occur, especially as jamesonite. The ores of this zone are frequently without gangue.

"E. The blende zone. (Principal zinc zone.)

"F. The argentiferous galena zone. Silver may fail in the galena. (Principal lead zone.)

"G. (G-H). The zone of silver and also much gold, usually associated with metals which combine with them to make substances which are undoubtedly highly mobile

[32] *Econ. Geol.*, Vol. II, No. 8, p. 791.

[33] *Econ. Geol.*, Vol. VII, No. 5, p. 489.

and account for the relatively elevated position of the zone. These associated metals include antimony, bismuth, arsenic, tellurium, and selenium. Characteristic minerals of this zone are tellurides and selenides of silver, gold tellurides, primary argentiferous tetrahedrite and tennantite, polybasite, stephanite, and argentite. (Principal silver and gold zone.)"

This sequence, of course, is that for the intermediate-magma-derived ore magmas (see Chapters XII and XIII): which is more usual and typical than the extreme (basic or siliceous) ore-magma sequences.

The above tentative deductions should be compared with those arrived at in the last part of Chapter XI, where the conclusion was independently deduced that there was a pressure limit for ore magmas within 500 to 1,000 feet of the surface; and that at that limit they disintegrated as magmas and were precipitated, whatever the temperature. But let us reflect that the temperature factor is important, for it determines what type of ore magmas will mount to the point where they are blocked by the pressure limit. With very high temperatures the whole complex ore magma, just as differentiated from the rock magma, will climb almost or quite up to the pressure limit, and we shall have such a complex representation of all the ore zones—such a fairly complete telescoped ore magma—as we find at Cripple Creek, for example (p. 548) and at Tonopah (p. 294). With a lesser temperature, only the silver zone (G) may climb to near the surface (as in the putative instances at Guanajuato and Divide—pp. 551 and 552); and the result is simply a rich and shallow silver deposit. And there will be intermediate cases, of course.

The mingled gold-silver quartz veins of evidently superficial origin continue to be the most perplexing phase of ore deposition; but more and more clearly seem to constitute a special phase of the phenomena above outlined. And I am—almost perforce—inclined to consider that they result in some way from the "intermediate cases" I mentioned

above—cases where the surface temperature, at the time of the injection upward of the composite ore magmas, was not of the hottest, so that, as at Aurora, certainly no telescoping of the whole metal scale occurred, or even of any part of it. On the other hand, the uppermost silver zone in these cases, as at Aurora, has been freely, even though irregularly, mingled with gold, in which the result separates itself from the Guanajuato-Divide type; and in accordance with all of my deductions, this access of gold must have come from the active ore magmas below, and by a process of selection.

This distillation or exhalation of gold from ore magmas (representing the normal deeper auriferous zones) in the vein type under consideration may perhaps also be a phenomenon of relatively slight pressure, due to relatively slight depth, even though deeper than the actual ultimate pressure limit for all ore magmas. To make this hypothesis clearer, let us suppose that the temperature at the pressure limit (say 500 feet below the surface) was about that of the deposition of the principal silver zone (G).[34] Then the underlying zones (including the auriferous zones B and D) would not ascend and perform telescoping, but would range themselves in order below, but with a minimum altitude for each zone, on account of the rapidity of increase of temperature downward, near the surface. The hypothesis supposes that at the still relatively shallow depths at which zones B and D would consolidate, the pressure would not be sufficient for the retention of the gold to the extent that it is at greater depths; and that under these nearer-surface conditions much of the gold escapes and rises till it also, like the silver, is precipitated very close to the surface. The mingling of normal silver-zone magma (G) with the exceptional gold-bearing magma solution (H), when both are still fluid, produces, according to this hypothesis, the silver-gold quartz veins, with gold and silver in all proportions. I am inclined to think that the quartz of the combination

[34] Say 400° C. See p. 834.

belongs with zone G and that the escape of the gold in question is not essentially accomplished by or in company with a silica solution. That is, I assume that we have at Mercur these two types of ore solutions (G and H), separate and distinct; but in many cases I assume that we have them mingled in all proportions. In some districts we shall, moreover, find the one without the other.

CHAPTER XVI

The Origin of Fissure Veins

This chapter sets forth that although a considerable proportion of mineral veins are veindikes—that is, that they are intruded under their own gaseous tension—while many have been formed by replacement or impregnation by thinner and more aqueous ore magmas, yet the locus and shape of all these veins is determined by pre-existing fissures in the rocks. Certain fissure veins are confined to the areas of restricted intrusive bodies, making it certain that the fissures were developed as the result of adjustment of the igneous rock after intrusion. Such fissures may cut across intrusive necks or bodies, from side to side, or form, roughly, parallel to the contacts. In some instances two sets of fissures due to adjustment of the intrusive rock have been noted within the rock, the major set parallel to the long axis of the intrusion, the minor set transverse to it. Fissures form along dikes; indeed, a fissure once opened is apt to be reopened; and this may give rise to compound veins or, indeed, to compound dikes. Usually the fissures which are filled by veins are of very slight relative movement or displacement. Where a vein occupies a fault of considerable displacement, it belongs in many cases to a later intrusion episode than the fault. But faulting may result from the upward and outward shove of intrusion, or, on the other hand, from contraction and sagging after intrusion; and in the former case considerable faulting may elapse before the ore deposition, and still the two may belong to the same intrusion episode. Horizontal movement is as common in faulting as the vertical, and often predominates. But the inception of the average fissure is probably from a vertically exerted force, as indicated by the very common dip of 60 to 70°. The common east-west trend of veins in the Western United States is perhaps due to the east-west trend of subcrustal magma invasions. Conjugated vein fissures are believed to owe their origin to force exerted by an intrusion, either upward or downward.

THIS CHAPTER IS, IN A WAY, partly a restatement of some of the conclusions arrived at in Chapter VIII, but from a somewhat different point of view. In general, I have assumed that magmas are, more or less, in a state of gaseous tension, by virtue of which they

differentiate and by virtue of which they have intrusive power; and this applies to all magmas, whether silicate magmas, which are the common rock magmas, or to those highly specialized magmas which are the products of differentiation, and which I have called ore magmas. The rock magmas are present in enormous quantity in many cases; they intrude as immense masses, and also as dikes of varying width. The ore magmas, like all extreme magmas, are produced only in small quantity; and they are characteristically intruded in dike-like form, which we may call veindikes or veins. It is likely that a considerable proportion of the mineral veins are not far different from the pegmatites in mode of origin, in that they are intrusive under their own gaseous tension, which has been strong enough to push the intruded rocks aside; and this is probably true at all zones of ore deposition. Not only the pegmatites, and the gold-quartz veins, but the tungsten-quartz, and the tin-quartz veins, show the characteristic features of this origin—frequent wide regular veins with parallel walls (which could never have represented the filling of pre-existing open fissures) and included angular unsupported fragments of the wall rocks. And the same features persist in the wide quartz veins of all stages, up to those in Tertiary lavas, such as I have described at Tonopah and Aurora. Such veins are often fifty or a hundred feet wide,[1] and very long and regular. Empty fissures of this size could never have existed. An origin of the veins by replacement is in very many cases quite out of the question, for the contact with the wall rocks is sharp, and the included fragments have not only sharp contacts with the vein quartz, but the original angular corners are not rounded by corrosion. The forcing apart of the walls of these veins by the pressure of crystallization

[1] There is an analogy between veindikes and dikes in this matter of width, as well as other characteristics. Note DALY, "Igneous Rocks," etc., p. 82: "The average width of mapped dikes is probably well under 100 feet, if, indeed, it is not less than 40 feet."

has been argued repeatedly, but the application of such a supposition is misty. In the majority of these cases the vein-quartz filling will be found to be homogeneous and granular. How did the filling get into the vein fissure before it crystallized, for obviously it all crystallized in place as we find it? No distinct analysis or picture of the workings of this crystallization hypothesis seems possible. The walls of the veins have certainly been thrust apart by pressure, but the thrusting aside was accomplished before crystallization; and the thrusting power, therefore, resided in the fluid quartz magma, which, accordingly, was under pressure, quite like the pressure of a rock magma which solidifies, after penetration, as a rock dike. Such pressure, I have assumed, depends on the gaseous tension which resides in the magmas in each case, on account of their being in more or less a gaseous condition, or partly made up of gaseous elements.

These characteristics, once grasped, and their significance as well, will be found to be true of many sulphide veins, as well as quartz veins, at all stages; and, moreover, of many veins of barite, fluorite, celestite, dolomite-siderite-magnesite-rhodochrosite, and even of calcite.

The above, while I believe it is most typical of veins, is not true of all veins. Many veins have formed, of course, by replacement along fracture zones, and by impregnation of porous zones or rocks of all descriptions. A difference in the aqueous content and in the gaseous nature and gaseous content of different vein magmas, even different quartz-vein magmas, must be granted, as deduced from these varying characteristics. Some ore magmas are more aqueous than others—consist more and more of water, and come accordingly to prefer to soak through broken rocks rather than to shove them asunder.

But it is apparent that even fissure veins, where there has been practically no replacement, and which are therefore veindikes, have found the rock pressure less along certain fissure planes or fractures, and so the ore magma has entered

and passed upward along these. An excellent example of this principle is shown by the distribution of fissure veins in a volcanic neck at Tonopah[2] (Fig. 119). Here is a neck of rhyolite, the vent of an old volcano, surrounded by older volcanic rocks, through which the neck has been forced. In this neck are many clear-cut fissure veins, increasing in number toward the contact and chiefly parallel to it, and sometimes occurring on the very contact. They are irregular and non-persistent, but are locally as much as 20 feet wide; and in no case do they extend into the intruded rock. In addition to these veins which bear a definite relation to the contact (most of which are not shown on the map), there is a prominent line of veins of the same type which cut straight across the neck, from contact to contact, as shown in the figure. The filling of these veins is brown and white calcite, siderite, and quartz; the white calcite is the most prominent. Many of the widest veins of calcite are beautifully banded. The vein filling followed definite stages. After an early slight silicification of the rhyolite walls, which does not seem to be much represented in the vein fillings, the first fissure filling was of mixed calcite and siderite; this was split open, and banded white calcite infilled; and finally this calcite was split open and relatively narrow veins of jaspery and chalcedonic quartz infilled (Fig. 120). Locally the white banded calcite carries angular fragments (Fig. 148).

The point to be made and held in mind about these fissure veins is that their distribution shows that they follow and, therefore, depend on the laws of strain. Firstly, they are confined to the volcanic neck, showing that they are due to adjustment movements in the neck after consolidation. The greater abundance near the contact and the tendency toward parallelism with the contact shows that these movements had to do largely with shifting of the position of the whole neck, up or down, with regard to the intruded rock; but the main vein zone traversing the neck

[2] *Professional Paper* 42, U. S. Geol. Surv., pp. 101-103.

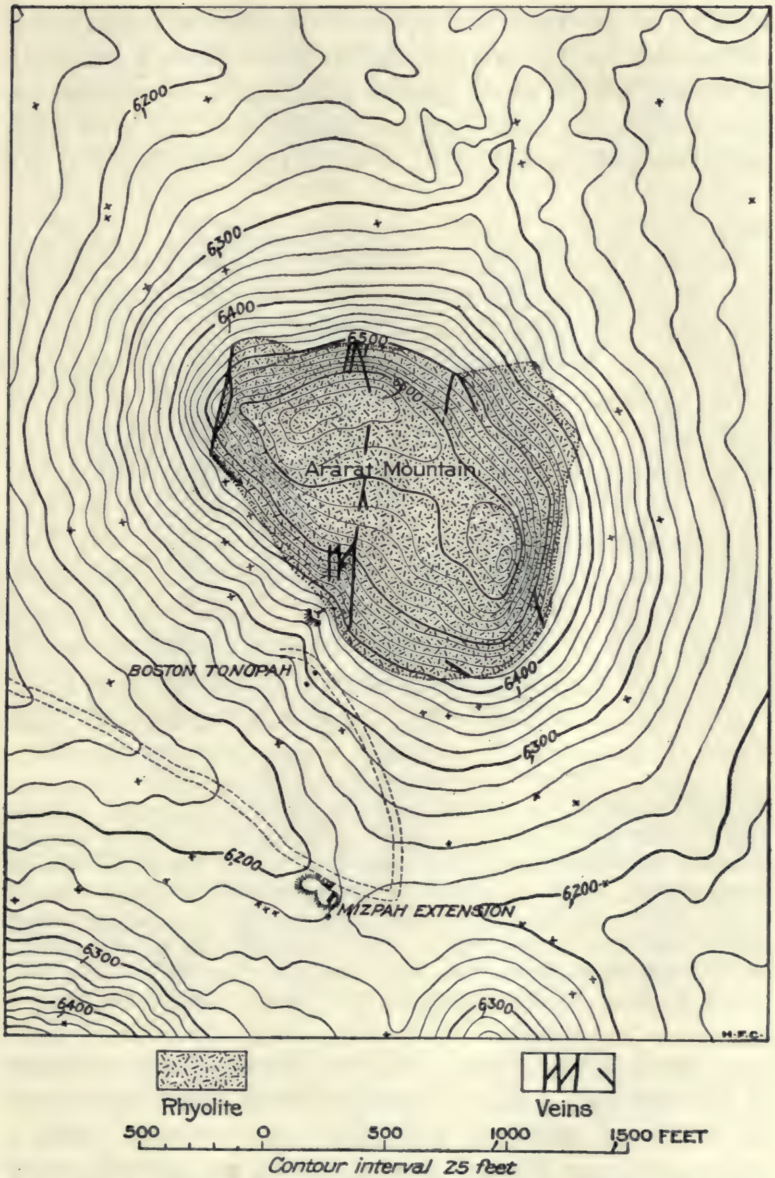


FIG. 119.—Tonopah, Nevada. Rhyolite volcanic neck, showing barren fissure veins of calcite and quartz. The rhyolite is intrusive into older volcanics. These fissure veins are confined to rhyolite; hence are due to strains connected with the adjustment of the rhyolite neck. After J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Plate XIV.

shows also movements dependent on internal adjustments of the neck; and in this case the fissures indicate a condition of tension which seems plainly attributable to contraction on consolidation, since they are parallel with the short horizontal axis of the neck. More than that, the detail of the

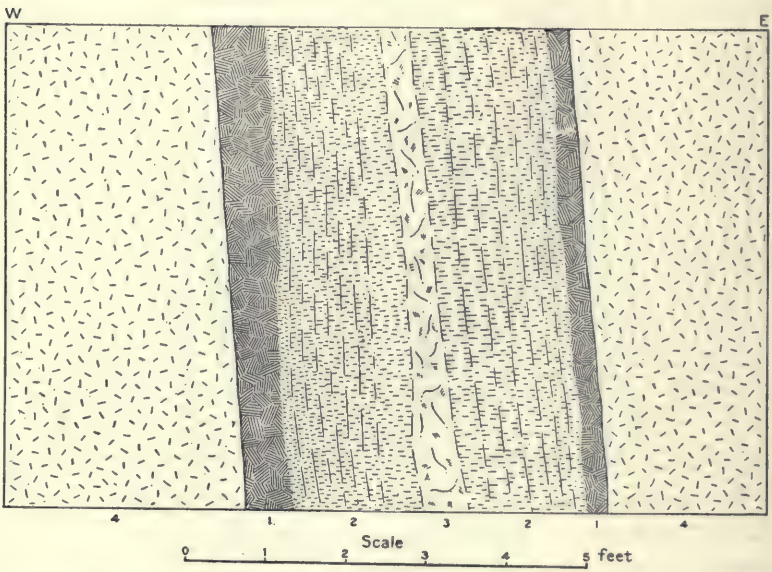


FIG. 120.—Tonopah, Nevada. Barren fissure vein in rhyolite neck. 1, Dark-brown calcite and siderite, mixed; 2, white calcite, beautifully banded; 3, quartz, mixed with calcite; 4, rhyolite (wall rock). Was this a yawning fissure through which the waters coursed, gradually building up deposits on the walls? The banded structure, and especially the fine banding of calcite, might denote this. But how shall we explain the included angular calcite fragments shown in a vein of this type a few feet away? (Fig. 148.) J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Fig. 14.

vein distribution follows the laws of strain. "Each vein can be followed only a short distance, when it becomes confused by reason of splitting, straggling, and thinning, while a lateral vein may thicken up so as to become of predominating importance."[3] Such characteristics represent the effect of strain; and, therefore, the position of such veins as this

[3] *Op. cit.*, p. 103

has been determined largely by tension due to contraction, resulting in a tendency toward actual fissures, which rendered very easy the injection of fluids under pressure. The pressure of the solutions from which the calcite was deposited helped to keep open the fissures, which probably would not have remained open otherwise. These veins occur in the volcanic neck only, for a double reason: that the volcanic rock, by its easing on consolidation, provided openings along cracks, and that the magma solutions were derived from the volcanic depths lower down. They are, of course, not really ore veins, although they are certainly magmatic: they contain no ore or sulphides, but they follow the same laws of strain. Note in the figure, the branching and joining habit, characteristic of the "linked-vein" type so often observable in shallow-formed veins.

Of this "linked-vein" type are most of the main productive veins at Tonopah (Fig. 115), but they are usually stronger individually, more regular in width and more persistent in their longitudinal extent than are the calcitic veins above described, which belong to a much later period than the productive veins.

The productive veins at Tonopah, it will be remembered, are quartz veins rich in silver and gold. Some of the most productive of these veins represent the silicification and replacement of sheeted zones of trachyte, originally marked by close-set parallel fractures, but not faulting (Fig. 121).[4] The ore-magma solutions in this case were then largely aqueous-gaseous. Since the strain-fracture zones which determined the location of these productive veins took place in a volcanic rock soon after consolidation, and since they are not faults, it is likely that in this case also the fractures were due to contraction and adjustment of bulk on cooling. Yet the tension resulting in the creation of these fracture zones did not necessarily result in open fissures—the veins were in part not deposited in openings.

The great majority of veins which show clear evidences

[4] *Op. cit.*, p. 117.

of fissure filling are, I believe, really veindikes, where the ore magma has been intruded: but even in these cases there must have been a varying ratio between tension or yawning tendency, due to contraction in the rock (or other causes) and the gaseous pressure exerted by the ore-magma solution; so that in some cases one, in some cases the other, was the predominating factor which produced the filling of the ore-magma solution into a fissure. When we come to

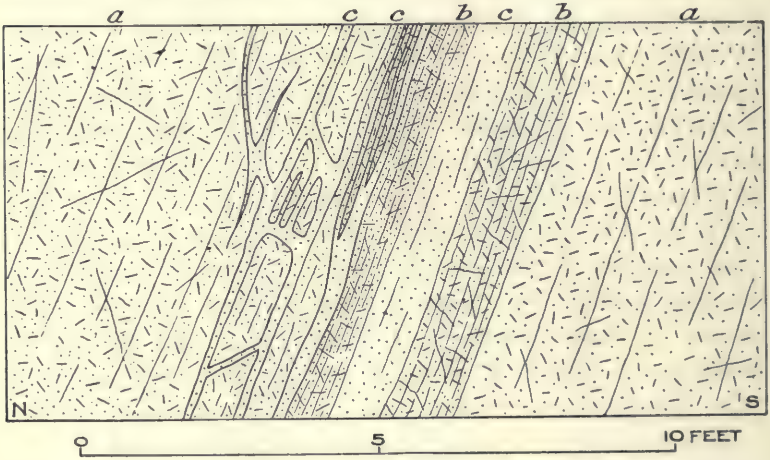


FIG. 121.—Tonopah, Nevada. Cross-section of Mizpah vein, sketched. *a*, Trachyte, wall rock; *b*, same, much silicified; *c*, quartz. Illustrates type of vein formed largely by replacement. After J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Plate XX D.

consider, we shall probably find that these factors are also true in most cases of dikes of true igneous rock.

At similar depths as have formed the typical principal productive veins at Tonopah, as above described, there were also formed at Tonopah a series of later quartz veins (but earlier than the calcite veins illustrated by Fig. 119), some of which appear to have formed by injection and not at all by replacement. Such, for example, is a great flat persistent vein of low-grade quartz, which follows a flat fault-fissure zone,[5] which appears to have been intruded under

[5] *Econ. Geol.*, Vol. X, No. 8, Dec., 1915, p. 736.

high pressure and to have the same intrusive power as an igneous sill would have had (see Fig. 33, p. 154). Indeed, it has the sill-like habit—persistent and wide, with none of the branching and interlocking features of the vein type induced primarily by slight strain fractures. It followed along a fissure created originally by strong faulting, but the flat nature of this faulting (which approximates the horizontal) shows that there could have been no tendency of the fissure to split or yawn, for it was pressed together by the immense weight of overlying rocks. From this we may deduce the further fact that an infilled fissure vein, due to injection, may arise from the seeking out, by an intrusive ore magma, of a fracture or fault fissure, of slight or great displacement, even when the rock pressure is exerted to keep this fissure tightly closed; for the very fact of the rift in the rocks still makes this fault comparatively the line of least resistance to intrusion.

Somewhat later, at Tonopah, came steeply dipping quartz-adularia veins, low grade or barren as to sulphides; these show no evidence of replacement, and the clean demarcation of vein from walls shows that the veins filled fissures; and the homogeneous crystallization of the veins, without banding or crustification, indicates that the opening of the fissure was accomplished by the pressure of the invading ore-magma solution, as it would be in the case of a dike. Such ore-magma solutions must certainly have been less aqueous than the type offered by the earlier veins in trachyte, above described; and yet the gaseous tension must have been adequate for intrusion.

Likewise, where quartz veins are regular, persistent, and up to 50 to 100 feet wide, with clear-cut lines of demarcation from the wall rock, as at Aurora, this represents a case of vein formation in a certainly superficial zone by the intrusion of a very slightly aqueous ore magma, highly competent as to gaseous tension. The ores are low-grade gold ores; and the vein habit is dikelike.[6]

[6] See p. 688.

A relation of mineral veins to an intrusive, similar to that of the rather diagrammatic one illustrated by the calcitic veins at Tonopah, is shown in Velardeña, Mexico.[7] I wish to speak of several groups of veins in this district. The first is the Terneras group. In an intrusive mass or neck of basic dioritic rock, elongated in a northeasterly direction, there are a series of parallel, persistent, and straight vertical veins, which run east and west and cut across the intrusive mass from side to side. When the veins pass into the intruded limestone on either side, they weaken and disappear (Fig 122). Considering that the easy replaceability of limestone makes it a very hospitable rock for the formation of orebodies—more, in general, than diorite—the limitation of the veins to the diorite is very noteworthy, and probably has a triple significance: first, that the vein fissures were due to adjustments in the diorite mass after consolidation; second, that the ore-magma solutions were derived from the magma of the diorite in depth; and third that the ore magma was relatively dry and aplitic, as in the case of the pyrite-pyrrhotite vein in the Potosi mine, in Chihuahua (p. 321). The linked type of veins is not here represented, but the long straight fissure characteristic of relatively considerable depth at the time of formation. The veins show both replacement of crushed rock and fissure filling, so the conditions represent a combination of the two types at Tonopah. The fissures were repeatedly reopened, and each time filled by new materials, so that the veins are compound (see pp. 269, 307). The earliest vein filling was quartz with copper-bearing pyrite; later came blende and galena; then argentiferous tetrahedrite, with overlapping and later carbonates of manganese, iron, lime, and magnesium; and finally calcite: all clearly magmatic stages. The fact that instead of thickening on entering the limestone, the veins branch and disappear, certainly indicates no very aqueous ore magmas; and those sections of the veins which represent fissure filling were probably

[7] *Econ. Geol.*, Vol. III, No. 8, p. 712.

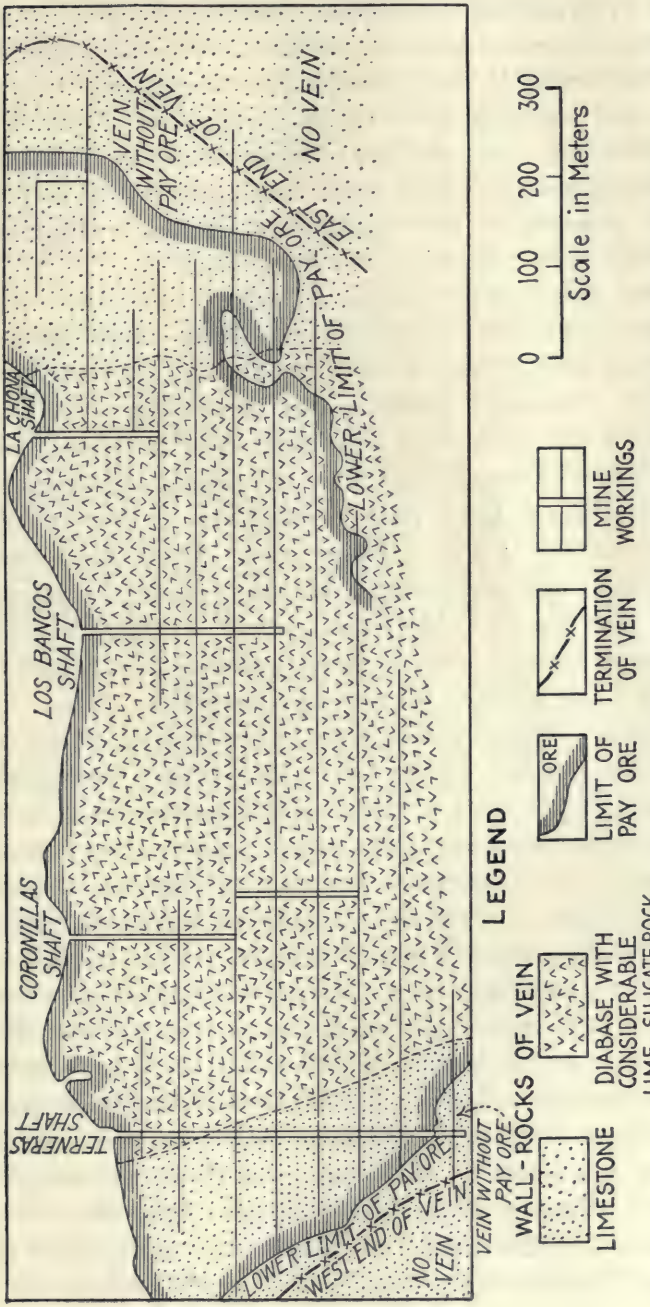


Fig. 122.—Vertical section on plane of Terneras vein, Velardeña, Durango, Mexico. Shows complete termination of very large and important vein on both ends in passing from diabase into limestone. By J. E. Spurr.

infilled by injection, the gaseous tension helping to create the fissure, together with the relaxation brought about by the adjustments of the underlying rock magma. One of these veins contains many angular fragments of the wall rock, showing at once the lack of replacement action by the vein filling, and probably some condition of viscosity or upward pressure in the ore-solution magma which kept these fragments buoyed up and suspended.

A few miles away, across a valley from the veins described, is the Santa Maria group—galena-blende veins in connection with a dike of trachytic alaskite intrusive into limestone. Zones of crushing and brecciation along the contacts of this dike show movement after intrusion, producing fissure channels; and there are similar slip channels in the limestone, but within a maximum of one or two hundred meters of the intrusive dike. These have been infilled, and limestone probably largely replaced, by galena, blende, and pyrite. Moreover, where a trachyte dike along whose contact a vein follows, makes a turn, generally the vein keeps straight on into the limestone. Now, this limestone is of the ordinary blue, heavy-bedded, fossiliferous variety, patently of the kind which is very susceptible to replacement in other districts; and the spectacle of lead-zinc sulphides traversing such a rock in regular veins instead of spreading out in irregular replacement deposits, such as we find so often in lead-zinc deposits in limestone, surely must mean, here in the Santa Maria also, relatively slightly aqueous ore magmas, as compared with which the ore magmas which have deposited lead and zinc at Leadville, for example, or at Aspen (in Colorado) must have been more tenuous or aqueous. In the case of the veins near the trachytic alaskite contacts at Velardeña, the gangue of quartz and calcite is important; but there has been no notable silicification of the limestone away from the veins; and the same is the case in the ore-bearing quartz veins in basic diorite above noted (the Terneras group), where they

run out into the limestone, branch, and die: the walls are regular and of blue limestone.

A third group of veins in Velardeña are associated with dioritic rock, but with an intermediate phase of it; and they are not far from the Terneras group. This third group, or Guardarraya group, of veins occur as definite but not very persistent veins along strong fractures near and usually paralleling the contact, but, as usual, were of development entirely subsequent to the consolidation of the intrusion. Such veins cut across irregularities in the contact, so as to lie now entirely in the igneous rock, now entirely in the limestone—which near the contact has been metamorphosed (metasomatosed) to lime silicates (not metalliferous)—or even in unaltered limestone. These veins carry chalcopyrite or cupriferous pyrite, blende and galena, arsenopyrite, and various gangue minerals. One regular vein of the usual fissure-like form lies entirely in unaltered limestone, a thousand feet away from the nearest portion of the intrusion. We find it interesting, apart from the fact of its lying in regular parallel limestone walls. The metallic minerals of the vein are pyrite, arsenopyrite, zinc-blende, and galena, in a gangue of quartz, calcite, and abundant potash feldspar (adularia). This is, of course, no superficial vein, but a fairly deep-seated one; so that we may note in passing that quartz-adularia veins are not confined to the shallow zone. Here, again, is evidence of a slightly aqueous, or relatively dry, ore magma—otherwise it would have forsaken the narrow channel of the vein, and would have irregularly penetrated the wall rocks of blue limestone, silicified them, and replaced them with sulphides. And the quartz, calcite, and abundant potash feldspar gangue shows an ore magma of chemical composition closely related to a pegmatitic or aplitic rock magma. On the other hand, some of the mines show orebodies which have been formed by the replacement of limestone along fissures; and which therefore were due to more aqueous magma solutions; of such nature is the main ore-

shoot of the Guardarraya mine itself (Fig. 123). The relation of these veins, near and parallel to the contact, shows, again, that the fractures were produced by the adjustments

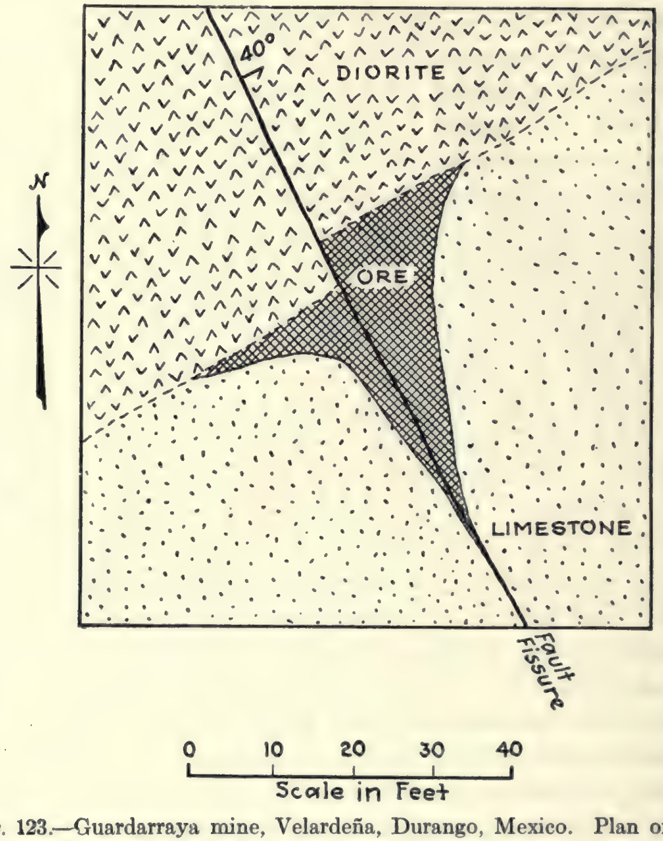


FIG. 123.—Guardarraya mine, Velardeña, Durango, Mexico. Plan of main oreshoot of mine, below second level. Shows localization of ore (lead-silver-zinc) by fault fissure on diorite-limestone contact, the ore being entirely in limestone. Thin ore-magma solutions ("pegmatitic," see Chapter VII) are evidenced, of a chemical nature so that limestone—not diorite—acted as a preferential precipitant—probably siliceous-alkaline solutions. This is in contrast to the aplitic type of solutions evidenced for the Terneras veins, only a few miles distant (p. 716).

of the intrusion, probably after consolidation. In the case of this Guardarraya diorite intrusion there is usually a narrow border of lime silicates, representing chiefly the metamorph-

ism, or, rather, metasomatism, of the limestone, along the intrusive contact; but this lime-silicate rock is not ore-bearing, and is very distinct indeed, and of a different age, from the later fissure veins above described. I might remark further that the basic diorite which contains the strong parallel cross-cutting Terneras group of veins (there are no veins near or parallel with the contact in the case of this intrusion) also is surrounded by its irregular aureole of lime-silicate rocks, quite guiltless of any ore deposition, and older than the veins. Indeed, the lime silicates have formed at the expense of the basic diabase as well (Fig. 55).

In this discussion of the origin of fissure veins I want to return again to the Matehuala (Dolores) district. Here in the main ore-producing area there has been a very irregular intrusion of monzonite into blue limestone, which intrusion, nevertheless, has a definite northwest longer axis of roughly 3,000 feet and more, and a transverse axis or width averaging perhaps 600 feet, more or less. The limestone and the monzonite have both been locally altered to lime silicates—garnet, pyroxene, wollastonite, and the rest—the usual phenomena of so-called contact metamorphism. The contacts have been carefully and instrumentally surveyed. I have presented a drawing (Fig. 53), showing the monzonite and the limestone, and also the monzonite which has been altered to lime silicates and the limestone which has been altered to the same lime silicates, to show the local nature and vagaries of the lime silication, and to show that this action is not due to water expressed from the igneous rock now exposed, at the moment of consolidation, but is due to magmatic solutions, assuredly derived from the monzonitic magma, but coming from greater depths, exactly in the same way as are derived the ore-magma solutions which form fissure veins. Now, I am also presenting a separate drawing (Fig. 124), showing only the monzonite and the limestone (not distinguishing in this case the metamorphosed portions of either), and the fissure veins. Although the older of these ores occur mainly at or near

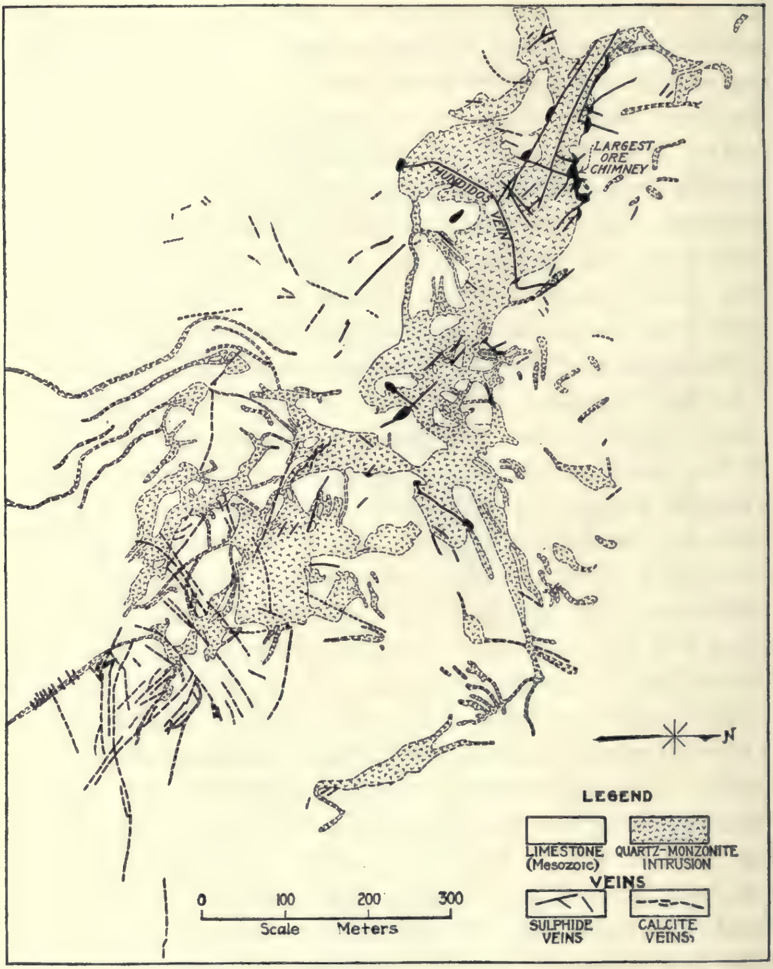


FIG. 124.—Matehuala, Durango, Mexico. Dolores mine and vicinity. Showing intrusion of quartz monzonite into limestone, and location and trend of subsequent fissure veins. These are confined to the intrusion and its vicinity, and occur in two predominant sets, one parallel to the axis of the intrusion and one transverse to this axis. There are also chimney-like and fissure-like ore deposits along some contacts.

the contact of monzonite and limestone, and have a gangue largely composed of garnet and other lime silicates, yet most of the ores are essentially in fissure veins, as the detailed studies and mapping of myself and assistants have shown. I have given details of the vein sequence in a former chapter. The lime silicates form usually irregular bodies in limestone and monzonite, and are essentially pre-sulphide and barren. The sulphide period followed close on the heels of the gradual and long-drawn-out lime silication, with its various stages,[8] overlapping very slightly back upon this silicate period. First came the copper stage—chalcopyrite and cupriferous pyrite, most important of all; then, in constantly dwindling importance, arsenopyrite, auriferous and argentiferous pyrite and pyrrhotite, blende and galena, and finally barren calcite. The metallic sulphide veins have a chiefly quartz-fluorite gangue, except the earliest copper-bearing sulphides, which have also special iron-rich pyroxenes, amphiboles, and garnets as gangue —hedenbergite, actinolite, and andradite. In all these stages are fissure veins, together with a great deal of replacement, both of limestone and monzonite. The fissures of the earliest (copper) stage formed parallel to the general trend of the intrusion, and the copper ore chimneys occur more or less along a contact (the northeast side); and the other (southwest) contact, only about 200 yards away, carries very little ore. The slightly later copper ores with the exclusive quartz-fluorite gangue occupy still more definite fissures; most of these were along the contact, and broke through and mingled with the slightly earlier cupriferous ores with some contemporaneous lime silicates, just mentioned; but some persistent fissures were developed in the monzonite. Among these latter the most important (the Hundidos vein) strikes at right angles to the intrusion and cuts across the whole intrusion, from contact to contact, and where it strikes the limestone on the side opposite from the main local ore

[8] *Econ. Geol.,* Vol. VII, No. 5, Aug., 1912, p. 477.

deposition, it widens out into a replacement deposit in the limestone and makes the most important orebody (oreshoot or "ore pipe") on that side. The cursory observer would unhesitatingly call this ore pipe a "contact-metamorphic deposit," but it is not. Within the monzonite the vein is a striking fissure vein, but not strong enough to be of economic value. The fissure has been several times reopened and cemented by metallic minerals of later periods of deposition. There are many other straight, well-defined, and fairly persistent fissure veins of this period in the monzonite. There are two sets, running at right angles, as shown on the map: both sets appear to be about equally strong. They do not make important ore in the monzonite, however, but only where they intersect the limestone: but they do not pass into the limestone beyond the contact.

Passing over the arsenopyrite period, which follows upon the quartz-fluorite-chalcopyrite, we come to the pyrite-pyrrhotite (sometimes arsenical) period. These iron sulphides, carrying silver and gold, also occur as fillings of typical fissure veins in the monzonite; these also form the same two sets of fissures, at right angles to each other, the northeast set, transverse to the intrusion, probably the stronger. Where these veins cut the limestone they open out into pipes of very much larger size than the veins, just as has been described for the copper-quartz-fluorite ore of the earlier Hundidos vein.

Finally, the ore of the blende and galena periods, which is subsequent but quantitatively unimportant, mainly fills reopenings of earlier fissures of both sets, whether transverse to the main trend of the intrusion or parallel to it. Last of all, came the barren calcite-filled fissures.

From the point of view of the origin of fissure veins, there are several things I wish to illustrate from the foregoing description and accompanying map (Fig. 124). Here are ore deposits ranging from copper ores with lime-silicate gangue to galena-blende ores and calcite veins, all confined to an igneous intrusion and its contacts, and all localized

by fissures which from their parallelism to the two main axes of the intrusion are plainly due to strain originating in the igneous mass subsequent to its consolidation—to contraction strains, evidently, since there is no faulting along these fissures. Thus, two sets of fissure veins have originated; and the repeated reopenings of the fissures have followed always the same general directions. Again we see that the orebodies have formed in and at the contact of the intrusion for two reasons—first, because of the ore magma having been derived in depth from the monzonitic magma, and second, because the settling, shrinkage, and consequent adjustment of the consolidated monzonite now exposed has produced the shrinkage cracks which afforded lines of least resistance to the upward-pressing ore solutions.[9] And we note the law that in an intrusive mass of elongated shape, two sets of contemporaneous veins may develop, at right angles to each other, and parallel with the longest horizontal axis of the intrusion, and the shortest, respectively. Therefore, where we find this fact of two sets of contemporaneous veins at right angles to each other, as we do in the Eden mine, in Nicaragua (p. 665), we may suspect that they may indicate the shape of intrusion of the volcanic rock in which they occur, although we may have no other evidence of this.

Another lesson to be learned from the Matehuala case is that pipes or shoots of ore, or orebodies on contacts, may be along fissure lines, and that the pipes, as in the cases mentioned above, may be due to the intersection of two governing elements, the fissure and the limestone contact, of which the sine qua non is *the fissure rather than the contact*.[10]

Here I am going to digress from the subject of vein fissures to contrast the evidence as to the aqueous nature of the ore-magma solutions at Matehuala and at Velardeña.

[9] And, third, probably on account of the heat of the igneous rock. (See p. 835.)

[10] Note the Guardarraya ore chimney (Fig. 123).

In the latter district we have noted that many of the veins are strongest and most productive in the igneous intrusive; on entering the limestone they disappear. In the former district we have noted that the veins are plain, but not important or productive in the igneous intrusive; on entering the limestone they swell out into orebodies or pipes which constitute the principal ore; and they do not occur in the limestone as fissure veins, as they do at Velardeña. This difference of behavior is characteristic of all the vein stages of the Terneras intrusive at Velardeña and some of the other intrusives, as opposed to that of all the vein stages of the Matehuala intrusion. There is no great difference in mineralogical character of the vein stages of the two districts. The Santa Juana vein of the Terneras intrusion crosses the igneous rock (*diabase or diorite*) for a distance of 1,500 feet, and runs into the limestone. The only oreshoots in this vein are in the diabase-diorite; there is no ore at the limestone contact, and the vein, dwindling in size, *branches and dies on entering the limestone.* The vein filling is arsenopyrite, pyrite, and cupriferous pyrite chiefly, carrying some silver and gold, and with a quartz gangue. The Roca Negra vein of the same group has the same general composition and (like all the parallel veins of this Terneras group) the same relation to diabase-diorite and limestone. The mineralization and stage of these veins is similar in general to the San Miguel vein at Matehuala, which is a transverse fissure vein in the *monzonite,* containing arsenopyrite and pyrrhotite carrying gold and silver, but *which only opens out into an important oreshoot at the limestone contact.*

Here then we have sufficient data to show that the Matehuala ore magma, with the same stage and type of metallic composition, was in general far more aqueous than the Terneras (Velardeña) ore magma; and that the Terneras ore magma was really a relatively dry one, since it did not combine with, permeate, and replace limestone when it came in contact with it. It was, indeed, of the

aplitic type, like that which formed the vein in the Potosi mine, at Santa Eulalia (Chapter VII); while the ore magma at Matehuala was of the wet or pegmatitic type. In line with this evidence is the occurrence of abundant fluorite together with the quartz, as contemporary gangue in the Matehuala veins; while the contemporary gangue in the Terneras veins is simply quartz. This established difference in the aqueousness of the magmas in the two districts shows that abundant water is not a necessary component of ore-magma solution, nor a necessary carrier of the metals, except doubtless in a certain minimum quantity; and this definite local evidence harmonizes with the general conclusions to the same effect that I have drawn in comparing the basic-magma-derived vein sequence (typically relatively very slightly aqueous) with the siliceous-magma-derived vein sequence (relatively more aqueous). Water and other volatile elements, as I conclude on these broader grounds, are an accompaniment, but not a necessary integral part, of sulphide ore-magma solutions or even of quartz-magma solutions, except, as again stated, in a very minor and limited degree; and we may and do, therefore, have the same earthy and metallic fissure veins formed from ore-magma solutions of all degrees of aqueous-gaseous dilution, ranging from relatively dry ore magmas toward relatively aqueous-gaseous ones.

In studying the dilution or aqueousness of ore-magma solutions, this test of replacement or permeation of limestone by them is probably the best, where limestone is present. Yet limestone does not afford the only test; the relative replaceability, and permeability, and alteration of other types of wall rocks affords also an excellent criterion. The lack of silicification of granodioritic wall rocks of quartz veins, as in the case of the quartz veins of California, surely denotes a dry ore-magma solution; just as does the comparative lack of alteration of wall rocks at Sudbury. The presence of inclusions, of wall rock of any type, which have not been replaced or much altered has the same signifi-

cance; and in general it is probable that unsupported fragments of wall rock in a fissure vein similarly indicate a thick and highly concentrated intrusive vein magma.

The limestone criterion may be applied in a way also to determine the relative amount of water. For example, the ore magmas which have been unable to replace or combine with limestone walls at Velardeña and at Santa Eulalia must have been less aqueous than those well-known pegmatites which occur in granites, but at their contacts combine with limestone to form lime silicates. This is, indeed, the ordinary type of pegmatite, so that the fissure veins which (as those at Matehuala) end in pipes in limestone, and so have what we might call the dumb-bell shape, seem to be comparable to pegmatites in aqueousness, while those of the Terneras type are seen to be more comparable to the aplitic magma in aqueousness. Of course, there are in the ore magma transitions between the two types. The comparison, however, is illuminating when we recall the fact that pegmatite veindikes are sometimes rudely banded, or may even have central vugs, due, I believe, to contraction of bulk on consolidation; while many injected fissure veins are homogeneous and have neither banding nor vugs; and when we realize that according to the above conclusions the magma of such pegmatites was more aqueous than that of such veins.

Somewhat similar to Matehuala, but on a smaller scale, is the igneous intrusion and vein system mapped by myself and associates at the Concordia mine, at Zimapan, Hidalgo, Mexico. The igneous intrusion (into limestone) was accompanied by the formation of lime silicates; but the ores, as shown, are fissure veins, one system running parallel to the long axis of the intrusion and one transverse (Figs. 125 and 126).

The principle of the preferential localization of fissure veins—whether formed by relatively dry, intermediate, or aqueous ore magmas—in rifts due to contraction and adjustment of intrusive igneous masses, finds a simple illustration

in the "ladder veins" frequently found, where transverse fissures in an igneous dike, due plainly to the contraction of the dike after consolidation, have been filled with vein material.

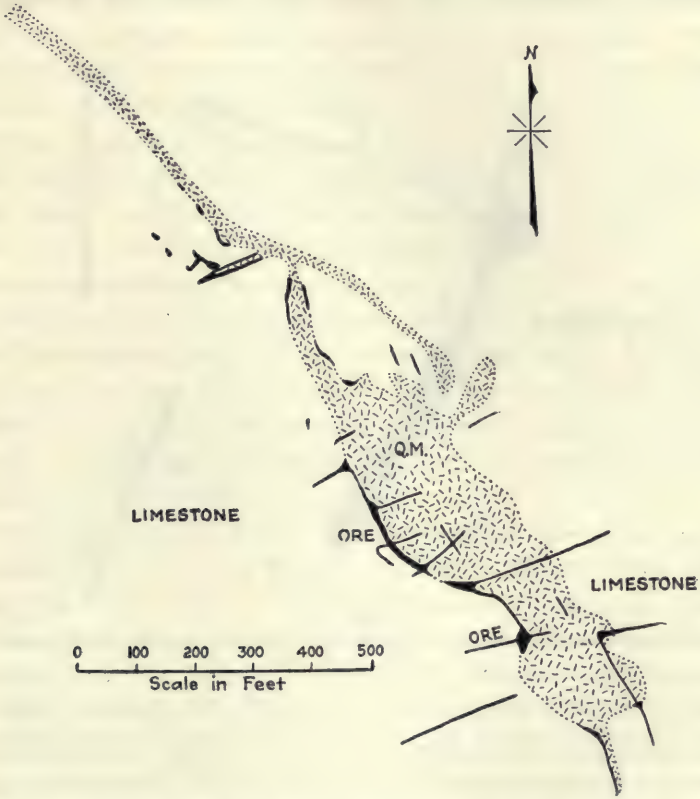


Fig. 125.—Zimapan, Hidalgo, Mexico. Concordia group of claims. Surface map, showing intrusion of quartz monzonite (Q. M.) into limestone, and veins and orebodies. Shows two systems of veins—one parallel and the other transverse to the intrusion. The concentration of ore along the hanging-wall contact of the intrusion (southwest side) indicates ascending ore-magma solutions. Plane-table geological survey by J. E. Spurr and G. H. Garrey, 1907.

Be it noted again, however, that the general rule (to which there are exceptions) is that only those contraction cracks and slight faults which are first formed after the

intrusion of an igneous rock become the channel for fissure veins, because the intrusion of ore magma typically takes place at a somewhat later period than that of the igneous rock, but represents a phase of the life history of the same intrusive magma as that which the fissured rock intrusion

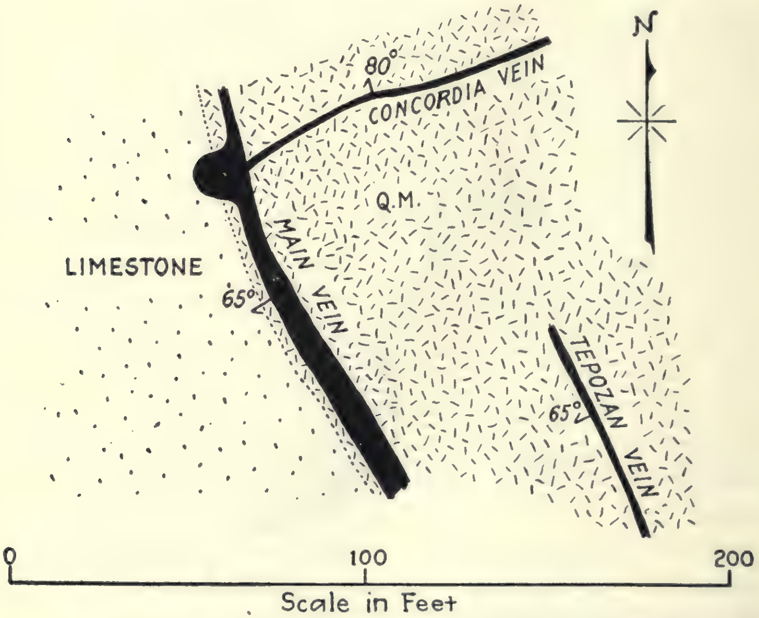


FIG. 126.—Zimapan, Hidalgo, Mexico. Concordia mine. Enlarged detail of Fig. 125, showing some of the most important veins. Note that the main (contact) vein has both walls in monzonite, the hanging wall being separated from the limestone by a thin slice of monzonite. Therefore, the vein is a fissure vein. Note, also, contact chimney formed by intersection of main vein with transverse Concordia vein.

represents. After the process of consolidation of the magma in depth has been completed, after the complete consolidation and differentiation of the magma in the deeper zones where the slow congelation is favorable to this separation out of certain rock elements to form extreme end-product magmas such as the ore magmas, then the process of ore deposition is at an end, and no matter how deep the subse-

quent fissuring runs, or how broad and inviting the fissure or fault zone for solutions, there will be found in all subsequent time none to enter it, none to cement it and convert it into a vein.[11] The process of vein formation, of ore deposition, is as definite as that of dike formation; it is a definite magmatic stage, the invasion along available channels of least resistance of an extreme type of magma which results from the consolidation and differentiation of the mother magma. Therefore, by the time that adjustment of the igneous rock, due to the shifting and ebbing of its deep-set plastic foundations, has proceeded far—before the long rifts, splits, and little faults have grown to be notable ones—in most instances the last stages of the intrusive magmatic episode are over, and these great and deep-reaching fissures will be barren, cutting the veins and orebodies—although the location and distribution of these faults also may point clearly to an origin connected with slow readjustment of bulk, weight, and pressure due to the inequilibrium set up by the intrusion.

More common than veins *across* dikes are veins *along* dikes. A rift in the rocks once followed by either dike or vein as the line of least resistance to intrusive pressure (the laws of intrusion of rock magma and of ore magma are thus seen to be similar or identical) still remains a line of weakness and of least resistance; and is usually made further inviting to later intrusion by renewed splitting caused by any general rock stress, tensional or compressive, or varying from one to the other. Therefore it is that we find so often compound veins (which too often have not been recognized as such) where successive ore-magma injections follow the same fissure plane simply because it remains the plane of greatest weakness and thus the plane of least resistance to invasion. Therefore it is, also, that veins frequently follow dikes; and, conversely, that dikes frequently follow veins; or even that veins and dikes

[11] This is the general rule. I have treated the exceptional classes of fissure veins elsewhere (p. 733).

alternate in their arrival and occupancy of the same fissure-plane. But all this dike, veindike, and vein intrusion will usually be found, taken altogether, still to belong to the general, geologically very brief, period of the complex results of a magma intrusion; and all to antedate in general the deeper fissuring and more marked faulting. There are, as will be logically foreseen without appealing to examples, exceptions to this rule, where considerable faults become the seats of fissure-vein cementation. Such will be the case not only for the cases referred to on page 356, but also where such faults antedate magmatic differentiation, being ancient faults and due to an elder cause.

Of course, many veins are not in the igneous rocks; they are in the intruded rocks, on their flanks, or above; and in the case of great batholiths whose tops are only gently domed, the veins which form above them by the passage upward of the ore magmas from the differentiation zone beneath may not even be closely associated with any igneous rock, unless there are upreaching tongues or dikes from the main mass. In these cases, however, it is likely that the movements resulting from the adjustments of bulk of the igneous mass or batholith will be the factor controlling the fissure systems, as before; for the differential collapse of an igneous mass will cause a corresponding movement in the roof which it supports. Instead of fissures due mainly to horizontal contraction, however, we shall have quite a different set and plan, whether in the intrusive neck or dome, or in the intruded rock laterally or above; and it does not appear easy to state any law for such fissuring of vertical subsidence, if, indeed, any exists. What type of radial and radius-connecting fissures may form in intruded rocks by the sag of a volcanic neck after intrusion is indicated in the faulting at Tonopah around the rhyolitic necks (Fig. 66), although in this case it happens that the fissures have not been vein-filled.

Granted that it is the rule that ore veins fill the first slight fissures formed by the first slight adjustments in or near an

igneous-rock intrusion, resulting from change of volume on consolidation, how shall we explain the rather common exception where fissure veins fill fault fissures of considerable age and magnitude?

In some cases the explanation is the existence of a very old and persistent plane of faulting. At Peñoles, in Mexico, for example (see Chapter XVIII), the fault zone is a major zone of differential movement at least as old as the diorite intrusion which initiated the magmatic history in this place. It runs along one side of the diorite intrusion (Fig. 152.) A cross-section shows the diorite relatively elevated by this fault, from which the strata drop down in successive blocks as the distance from the diorite increases. The earlier (blende, galena, arsenopyrite, cupriferous pyrite) veins followed these fissures, but how much faulting the fissures then represented we do not know. When, at the far later—millions of years later—volcanic period, the silver veins occupied fissures caused by a renewal of faulting along the same zone, these faults represented the total amount of faulting at various epochs since the initial disturbance. The same fissures having been reopened yet again, and filled by barren calcite-siderite veins (and stibnite-bearing veins), these now occupied faults of much greater displacement. And subsequent to all vein-filling the faulting along these planes has continued. Thus it happens that in the Jesus Maria vein, where the earliest vein (sulphides, as above) has been reopened only once, and that prior to the last stage of the barren-gangue veins, when the fissure was infilled with a wide vein of dark ferriferous calcite, forming altogether a compound vein: the somewhat paradoxical condition exists that the sulphide portion of this compound vein occupies a fault of less magnitude than the calcitic portion—and yet both occupy the same fault. Therefore, at Peñoles the calcitic veins and the stibnite-bearing quartz veins occupy some considerable faults, while the same type of veins at Ojuela (thirty miles away) occupy the normal type of fissure of slight displacement, showing

that the reason at Peñoles is the anciently pre-existing fault which did not exist at Ojuela—and that the amount of movement which immediately preceded the vein at Peñoles, and which furnished the fissuring necessary for its penetration, was probably also very slight and quite within the rules.

We see, then, in considering vein and fault fissures, that we must distinguish between two classes: first, magmatically related fissures (i. e., where both fissures and ore deposition are related to the same igneous intrusion); and, second, independent and pre-existing fissures, where the ore deposition is genetically related to a certain igneous intrusion, but the fissure which it occupies is not so related, but is an earlier phenomenon, more directly related to some preceding and (for the purposes of our discussion) independent event.

I am not strong for coining new terms, and I think I have not done it, to any culpable degree, before in this book: but if I propose nothing new in the way of nomenclature, I may be open to the suspicion of not being erudite. Therefore, I shall call veins which fill fissures which are immediately related magmatically to them, *domestic veins,* as occupying their normal home or domicile; and those which have been lucky enough to find more ancient fissures already made, but not directly connected with the intrusion which was (according to my theory) the prime associate and next of kin of the ore deposits, *immigrant veins.* It is perhaps a poor choice, but you will get what I mean, and any term is simply a convenient handle whereby to grab a playfully elusive thought. If the handle enables you to catch it, it is a good handle.

Following out this thought, I think nearly all fissure veins which occupy fissures of slight displacement will be found to be domestic veins. All "linked veins" will, I believe, belong to this type, for this coarse net of slight fractures plainly is typical of the early stages of fissuring strain, with a broad zone of cracking, but little displace-

ment anywhere. And in each such case, we must look for some definite igneous intrusion as the nearest relative of both fissure and filling.

On the other hand, I think that, in general, fissure veins which occupy pronounced faults are immigrant veins; and we must look for the fissure filling to some directly preceding igneous intrusion, and for the fissure itself to some earlier and not so directly related cause. The immigrant vein will accordingly be straighter, longer and deeper; on the other hand, we shall often find that the house is too roomy for the immigrant, and that the ore and gangue have been able to occupy only certain sections of the fault fissure —certain rooms in the big house—where it was easiest to penetrate, leaving the rest of the fault fissure very slightly mineralized or barren; a long and weary fissure for you to drift, raise, and sink upon, looking for good orebodies.

I have contrasted the stibnite-bearing barren-gangue veins at Ojuela and at Peñoles, some thirty miles apart, as domestic and immigrant fissure veins respectively. In Colorado, the great silver-lead camps of Leadville and Aspen belong to an intermediate type, the ores having formed in each after some faulting, while the post-ore faulting was very great. The ores in these districts do not occur as fissure veins, but as replacements of limestone. But since fissures have served for the passage of the ore solutions, and the orebodies naturally maintain a relation to these fissures, the same comparative classification holds. At Leadville, as I have shown (p. 353, Fig. 68), the ore came up along faults, which in the only case I have been able to arrive at definitely, had a vertical displacement of about 100 feet, and spread out, and replaced limestone under relatively impervious blanketing layers (afforded by intrusive sills or sheets of porphyry, or dense sedimentary beds); and the heavy faulting, which succeeded, faulted these ore layers. If, in the course of ages, at Leadville, a new epoch of ore deposition had supervened, the new ore solutions would certainly have made use of these later

faults and formed new immigrant veins. The profound post-ore faulting at Leadville probably represents the continued uprising of the magma beneath, for the faults are part of the recent uplift of the range (Mosquito range) on whose western slope Leadville lies.

We may compare the history at Aspen very instructively. Here we have the same geologic formations—pre-Cambrian, Paleozoic and Mesozoic—as at Leadville; and the "white" porphyry or alaskite porphyry intrusion, as dikes and sheets at Leadville, is similarly found at Aspen, but is quantitatively of far less importance. The "gray" porphyry or monzonite porphyry dikes and sheets, very abundant in Leadville (being there subsequent to the alaskite porphyry, but antecedent to the ore deposition, and so most closely connected, chronologically, with the latter), are not found at Aspen; but there is a scanty representation at Aspen of diorite porphyry, which is not related to the monzonite porphyry of Leadville, but is an outlier of a third great intrusion—that of the Elk Mountains, west of Aspen, while Leadville lies to the east of Aspen, with the Sawatch range and the Arkansas valley between. This diorite intrusion has, so far as I know, no attendant ore deposition—certainly nothing of importance. But the diorite intrusion of the Elk Mountains was probably the cause of a strong lateral thrust against the rocks of the Aspen district, which resulted in narrow close folding, culminating in faulting. At the same time there was an uplift of the Sawatch range, on whose western flank Aspen lies; and this up-ended and dragged up past one another the sedimentary beds (Cambrian and younger) which lie above the pre-Cambrian granite, producing very extensive bedding faults.[12] Such an uplift, I have assumed (p. 193), as probably due to the surgence in depth of magma which did not reach the surface. This surgence was also evidenced by a local doming-up, accomplished largely by faulting, at Aspen, and so representing on a small scale the same dynamic history and

[12] See Chapter VIII.

the same underlying cause thereof as the doming-up of the Mosquito range; or indeed of the Sawatch range.

The ore deposition at Aspen arrived only after considerable folding and faulting; therefore, the orebodies occur along or near considerable faults, and there is also, as at Leadville, a great deal of strong post-mineral faulting. In one case where measurements were possible, a fault—the Clark fault—had a pre-ore-deposition vertical component of movement of 250 to 350 feet, and a corresponding post-ore-deposition movement of 400 feet; so that the brief and critical period of vein deposition (although with a definite sequence of three typical magmatic stages—see p. 357) was fairly in the middle of the faulting, though nearer the beginning. At Leadville, the ore deposition, though in the faulting period, was still nearer the beginning. At Aspen the vein stages are the reverse of normal, beginning with the barren-gangue stage: 1, Barite; 2, the rich silver zone (silver sulphides, sulphantimonides, and sulpharsenides); 3, galena and blende; which clearly indicates a rising instead of a falling temperature, and so ore deposition during a period of magma surgence;[13] and the upgrowth of the local dome, referred to above, indicates that the magma plug or column kept right on rising after the ore deposition.

This may be the explanation, in this case, of the faulting which preceded the ore deposition. The first faulting, due in large part to the forcible uplifting and shattering of the superficial crust by the uprising of a magma column in depth making way for itself (at a greater depth this shoving away of the intruded rocks would have been accomplished more and more by folding, and at a still greater depth and pressure by that relatively cold flowage which produces schistosity and gneissic structure), took place when the horizon of the present Aspen ores was below the temperature limit of all magmatic vein deposition; but with increasing temperature due to the welling upward of the magma column in depth, the barren-gangue temperature stage was

[13] J. E. SPURR: *Econ. Geol.*, Vol. IV, June 1, 1909, p. 319.

reached, at which time the various sulphide stages were represented at successively greater depths; and with further rise in temperature, due to still further progress upward of the magma column, the ore zones also migrated upward, so that the uppermost sulphide zone (the rich silver zone) and later the galena zone arrived, and were successively superimposed on one another, so that the three stages occupy now the same horizon. This closed the ore sequence: the lower zones—arsenopyrite, copper, or gold, for example—are not represented; hence we may assume, at the end of the galena-blende deposition at Aspen, a marked fall of temperature due to the refrigeration and consolidation of the magma column.

But the continuation of the upward doming movement at Aspen shows that after the consolidation of this column down into the middle depths, the balance of pressure between the magma body in its ultimate depth and the overlying weight of rocks had not yet been restored, so that the magma pressure at the base of the intrusive column responsible for the ores (through its differentiation at the critical differentiation zone) has kept on pushing upward the column, and further breaking the superficial crust along fault planes. Say, rather, more accurately perhaps, that the intrusion did restore equilibrium between magmatic (telluric) and gravity pressure, but since the intrusion was slow and gentle, it only established it nicely and with precision; and that with continued erosion, in this mountainous region of relatively rapid lightening of the surface by atmospheric stripping, the relieving of the gravitational pressure was a continuous process, to compensate for which the underlying magma surgence proceeded step by step, and in conformity. This is suggested by the conclusions at Aspen that the local up-doming has kept pace with erosion, and is still progressing (p. 192).

This balanced equilibrium maintained by steady activity of a deep magma body in rising to compensate for erosion is, as I have argued, probably the chief instrument of

isostasy, over wide areas or very locally. As I have tried to show, however (p. 235), the underlying magma body is not always uniformly active to maintain equilibrium; on a continental scale, erosion often progresses till the equilibrium is quite unbalanced, before there is a migration of the deep magma to compensate it. This is doubtless due to the necessity of slow lateral flow of the deep magma horizon from under the oceans to under the continents. I have suggested, however, that when the magma tide does arrive, its momentum is such that the equilibrium is not only quickly restored by the addition of magma and consolidated igneous rock to the column where underlying telluric pressure had come to be in marked excess, but the scale is quickly swung the other way, so that the gravitational pressure of the crust column in question becomes in excess, resulting in settling, with the attendant faulting.

The same principle will apply in detail, in the consideration of a limited area or of a magma column or pipe of limited cross-section. If the intrusion is rapid, especially if it reaches the surface, with the consequent rapid transfer to the upper portion and top of the crust of a great weight of inert cold igneous rock (for while live magma presses up by its gaseous tension, dead magma or igneous rock presses down by its weight), then the equilibrium will be upset by the preponderance of gravity pressure, and the subsequent and long-continued faulting will tend to let down the top of the igneous column and drag down the surrounding rock.

The originally overlying cover of older rocks will have been entirely thrust up or aside, or put under severe compression to make way for the inthrusting magma column; so that at this stage there will not likely be any lateral fissures under separating tension. Among the first lateral and internal fissures to be marked by separating tension, and, therefore, sought by ore-depositing solutions of all the types I have described (sulphide magma, later earthy mineral magma, and still later hot magmatic waters), will be

those due to contraction and settling of the igneous column on consolidation; and the normal sequence will be: 1, slight fissuring; 2, ore deposition (domestic veins); 3, long-continued faulting as the adjustment under excess gravitational stress continues.

But in the case of an intrusion which does not reach the surface (as at Aspen), its upward pressure, especially when it arrives at a zone in the crust where the resisting gravitational pressure is not so great as to produce flowage (by schistosity), instead of breakage will create a tension in the overlying crust, which will separate it into fault blocks that will keep moving so long as the upward movement of the magma, or of the consolidated plug propelled by underlying unconsolidated magma, continues. Where an intrusive is broad and dome-shaped—the favorite form at considerable depths—large areas of the overlying crust will be thus under tension and subject to faulting. Two types of faulting resulting from intrusion are then likely: that resulting from the excess of the gravitational pressure, and that arising from an excess of the uplifting telluric pressure, the first marking local or regional sinking of the crust, the second marking local or regional uplifting of the crust. The first will be more characteristic of volcanic regions, where the magma intrusion has been violent and an outlet to the atmosphere has been established; the second in regions of intrusive rock, and in the case of magma movements upward which have not reached the surface. We might give this uplift-faulting the name *intrusion-faulting,* and the result of the opposed gravity-pressure excess, *adjustment-faulting.*

All the above discussion of uplift-faulting (intrusion-faulting) and adjustment-faulting sounds like vertical movements in either case. Not so: the facts do not correspond. There is much faulting in a horizontal direction. In many faults, the horizontal component of movement exceeds the vertical, although as a matter of fact the actual

net direction of differential movement varies from vertical to horizontal.

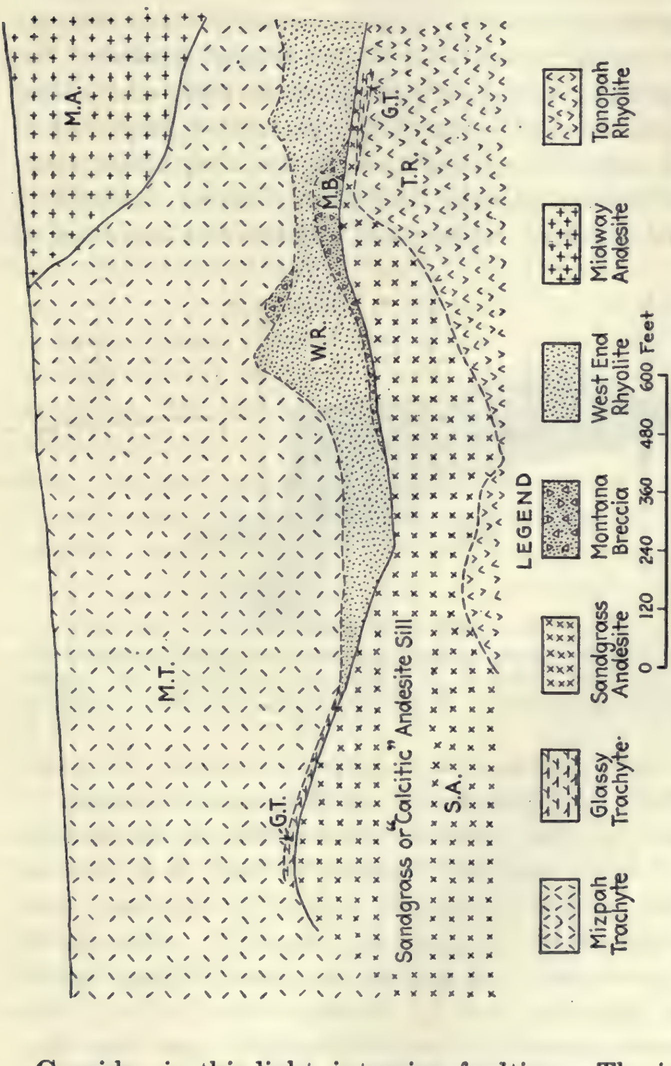


FIG. 127.—Vertical section at Tonopah, showing successive nearly horizontal intrusions and flows. The relative age is the same as the order of the legend. The Glassy trachyte is the basal phase of the Mizpah trachyte, which was a flow. The next three lavas were successive intrusions. The Midway andesite was a flow, the Tonopah rhyolite (latest) an intrusion.

Consider, in this light, intrusion-faulting. The intrusion of a magma column creates on its sides, if these sides are vertical, a horizontal thrust, and that thrust may be far transmitted; on the top, a vertical thrust; in the case of a

dome-like or rounded intrusion, it creates thrusts all the way from vertical to horizontal, on segments of the intrusive margin lying between the apex and the sides. Moreover, igneous intrusions do not necessarily come straight up: they avail themselves of the easiest channels, the natural easiest direction of parting of the rocks which they must penetrate, and as they near the surface they tend to slip from under excess weight caused by topographic elevations, and travel laterally to points of egress to which is interposed the least resistance. I have been surprised at

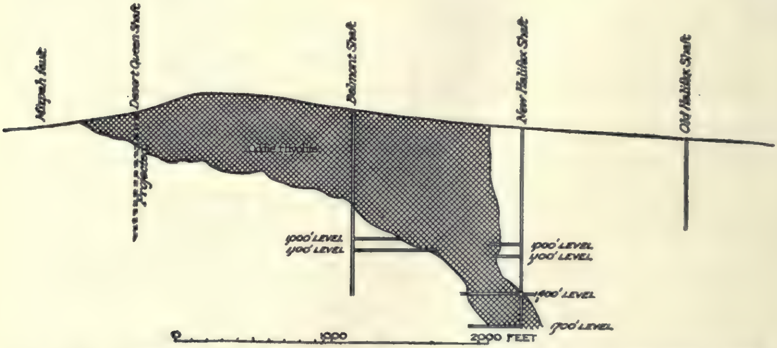


FIG. 128.—Tonopah, Nevada. Shows cross-section of rhyolite volcanic neck (intrusive into older volcanics), as actually determined by mine workings of Halifax and Belmont mines. Note strong horizontal element of intrusion.

this tendency among near-surface intrusions at Tonopah, which tend to approach the surface at a flat angle. I recommend in this connection the study of the geologic sections I have made at Tonopah,[14] where in a series of exclusively igneous rocks, the successive intrusions have been largely nearly horizontal (Fig. 127). One of the clearest cases—but not one of the most striking—is the volcanic (rhyolite) neck of Mount Oddie.[15] (Fig. 128.) The intrusive shove or strain of this neck must have been as much horizontal as vertical.

The faulting stresses of any unconsolidated magma body

[14] *Econ. Geol.,* Vol. X, No. 8, Dec., 1915.
[15] *Op. cit.,* p. 747.

(intrusion-faulting) may be resolved into two elements. First, the pressure on the walls, and perpendicular to them, due to the telluric pressure which accompanies and causes intrusion. On vertical walls, the pressure, as above noted, will be horizontal: on horizontal walls, vertical, and so on. Second, especially near the surface, the drag of a viscous consolidating magma, which stress will be in the intruded rocks, in the direction of the intrusive flowage. Tonopah again offers a classic example, in the case of the Tonopah rhyolite, a great rhyolite mass which has come from the depths flatly and obliquely to the present surface (Figs. 129 and 130). "All phenomena indicate clearly a rhyolite glass intrusion, forced upward slowly and spasmodically, with partial stiffening in the intervals between the flow-movements, so that the congealed portions were repeatedly shattered and borne on as inclusions in the still fluid glass, which was itself stiff enough to disrupt in many cases even its own small phenocrysts."[16] I can visualize such an immense mass as this, of which the upper surface is only gently inclined, carrying forward on its back a great mass of overlying rocks, sufficiently so that the horizontal migration of this portaged overlying block might cause extensive horizontal faulting, even perhaps the astounding thrust faults that we find repeatedly, in which one block has been thrust over or under another, sometimes for miles.

The case of the isolated Sheephole Mountain, in the Mojave Desert of California, ten miles south of Amboy, is unique in my experience, and, being unique, is unusually instructive. I made only a brief visit to it in 1913, and therefore have hesitated in using it as an example: nevertheless I give it with the confession of hasty observation, and the consequent warning. The range strikes east and west, and I am showing here two sketched cross-sections, a quarter of a mile apart, cutting north-south across the range (Figs. 131 and 132). The uppermost formation is a basic overlying sheet of igneous rock, regularly overlying

[16] *Econ. Geol.*, Vol. X, No. 8, Dec., 1915, p. 748.

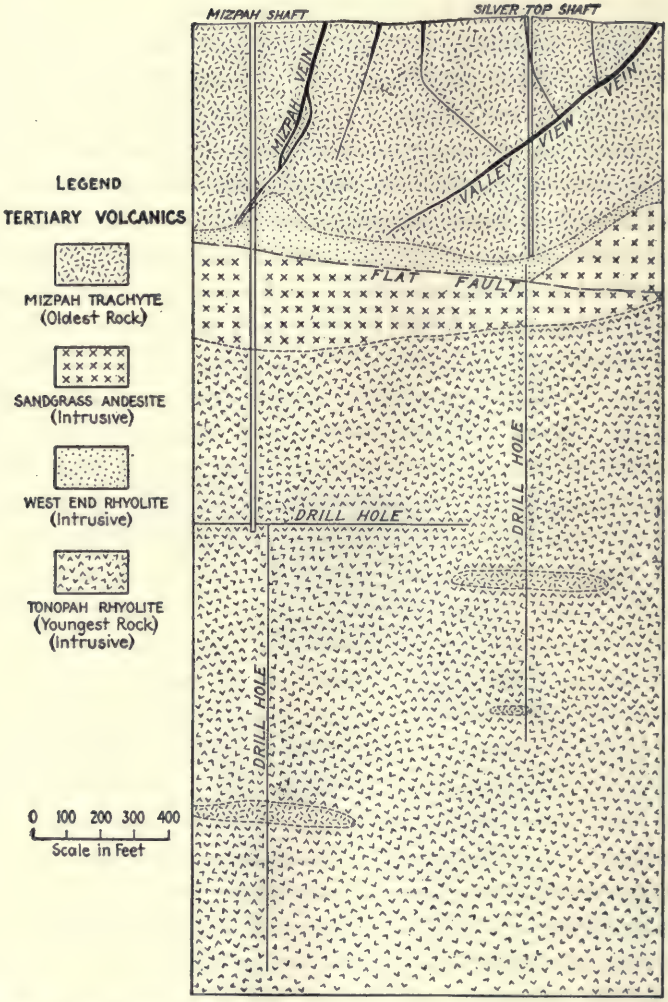


FIG. 129.—Deep section through Tonopah mine, Tonopah, Nevada; showing successive intrusion, of vein-bearing trachyte, by flat horizontally moving masses of later volcanics. The latest, a rhyolite breccia, has an immense but undetermined depth. It is the youngest of the rocks in the section. Section shows also characteristic flat faulting. By J. E. Spurr.

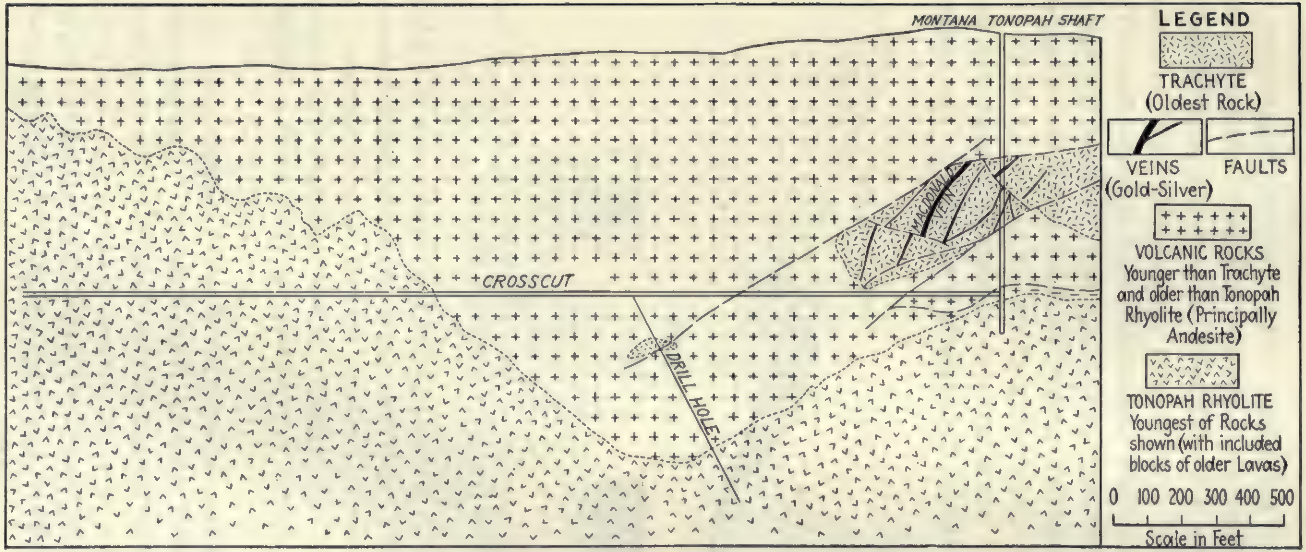


FIG. 130.—Montana Tonopah mine, Tonopah, Nevada. Cross-section of mine and long exploratory crosscut. The geology is generalized somewhat from the original section, for clarity.

The engulfment of a relatively small trachyte block, with its veins, in successive floods of lava, is shown. The Tonopah rhyolite is a remarkable intrusion. The portion designated as "Volcanic Rocks" is a complex of volcanic intrusions and a great surface flow.

The origin of the faulting which displaces the Montana veins is clearly due to the shoving about by the incoming subsequent lavas and their later adjustment. By J. E. Spurr.

and dipping away from more siliceous igneous rock, which forms the core of the range. The overlying basic sheet, as seen from a distance, appears a recent eruptive; but, examined near to, is a diorite of deep plutonic habit, showing variations of texture and composition due to differentiation *in situ,* and pegmatitic and aplitic dikes. The siliceous igneous rock underlying and forming the whole heart of the range is a typical alaskite, which in its uppermost portion is quite fine-grained for a zone of 50 to 100 feet, and lower down becomes unusually coarse and granitic. Hence, plainly, the alaskite is intrusive. The bottom

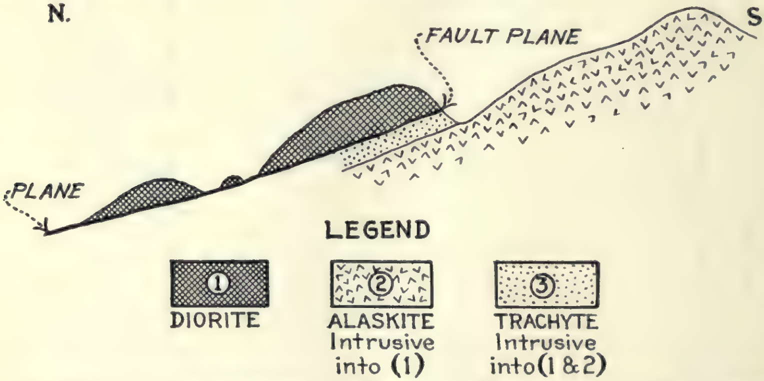


FIG. 131.—Partial cross-section of Sheephole Mountain, Amboy, Arizona. Sketched and generalized. See text.

of the diorite for a zone 50 to 100 feet thick, over the whole range, where observed, has been sheared parallel to the bottom of the diorite contact, and rendered schistose. As the upper part of the alaskite is not schistose, this contact effect in the diorite was evidently due to the alaskite intrusion.

At various places along the sheared diorite zone, gold deposition in small amounts was observed. The most conspicuous is at the America mine, where the ore solutions came up along east-west fissures, dipping 70°, for a belt a hundred feet or more wide, and cutting across the barren diorite schist. This gold deposition is accompanied by

extensive silicification; but the fissures are weak, and the mineralization does not go up into the solid diorite. At this mine, the underlying alaskite is not exposed, so that it is not known whether the ore goes down into the alaskite below.

Subsequent to the ore deposition, there was an intrusion of a sheet or sill of trachyte rock, consisting apparently of alkali feldspars and very little else (though in places some

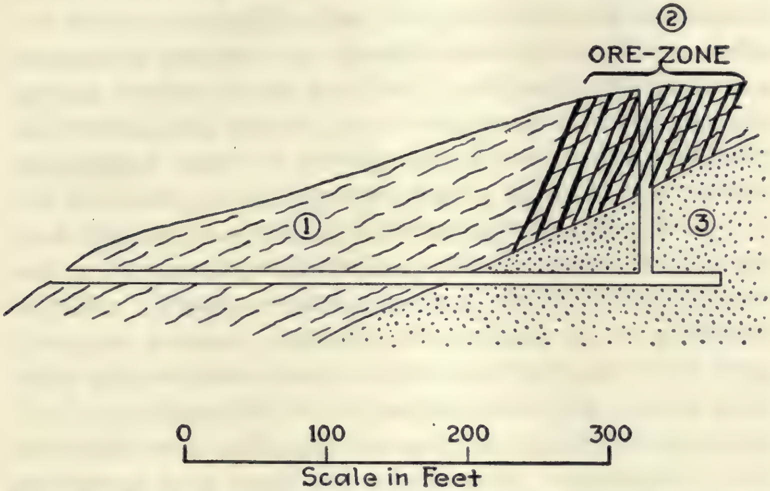


FIG. 132.—Sketched cross-section of America mine, Sheephole Mountain. The outer part of the tunnel is in the schistose belt (1) of diorite, which, with a thickness of one hundred feet or so, lies at the base of the diorite. The ore zone (2) is caused by the intersection, with this belt, of 70° dipping fissures. The trachyte (3) is subsequent to the ore, and cuts it off.

quartz comes in), showing a tendency to verge toward alaskite. This quite regular sheet, 100 to 150 feet thick, has been intruded along the contact of the sheared diorite with the alaskite, and sends steeply dipping small dikes through the overlying diorite. This trachyte is distinctly later than the ore at the America mine, which it cuts off cleanly.

The contour of the underlying alaskite is such that the range, at least on the two sides from which I viewed it,

has the form of an upthrust dome, the overlying diorite dipping away on the flanks of the range into the plain, exactly like a recent eruptive, while the siliceous igneous rocks emerge beneath it and form the core of the mountain.

To the common or garden physiographer—indeed, I confess, to my eye also—the range would seem recent, "as judged" (as I first noted from a distance) "by physiographic and erosion features." The dome structure is not seriously marred by erosion; and if the overlying rock had been basalt and the underlying one earlier rhyolite, none of us—even myself—would have hesitated in considering the dome a geologically recent one. But a study of the rock geology makes this view doubtful. Both diorite and alaskite are plutonic rocks, which crystallized at very considerable depth; the alaskitic magma forced itself powerfully into the diorite, along a horizontal rift, with such dynamic force that it sheared the diorite, parallel to its contact, for a zone 50 to 100 feet thick, but no further. Directly after the intrusion, came residual ore solutions, carrying silica and gold, from the alaskite, rising up along steep fissures which were plainly due to the adjustment of the alaskite on cooling; and on striking the schistose zone they were blanketed and precipitated. Then, along this shear-zone contact, an astonishingly regular and persistent intrusion of trachyte came, clearly a differentiation product of the alaskite magma, and, therefore, fixing the ore solutions as also within that category. Afterward, a certain amount of faulting, some of which I have shown in my section. This faulting is clearly "adjustment" faulting, due to gravity—the sag of the alaskite magma dome after intrusion—but some considerable time after, it will be observed. True to all the laws I have pointed out (p. 347) these faults are not only later than the mineralization, but the trachyte intrusion intervenes, a phenomenon not very frequent but still one of which other instances could be cited.

These two great regular layers of igneous rock—diorite and trachyte—overlying a third igneous rock (alaskite) as

if in normal order of outpouring from the bottom up, but having the order of age from the bottom up of 2, 3, 1, remind me quite strongly of the phenomena at Tonopah, where the roughly flat-lying succession of volcanic rocks has been by no means piled up by superposition, but thrust in as successive sills, generally one below the other; and a great flat-lying shear zone has played a large part in determining the advent of these sills, as in the case of the Sheephole range it has done, certainly for the trachyte.

Again, I must point out that the powerful lateral and nearly horizontal drag of the alaskite on the overlying diorite, evidenced by the shear zone, may well have been originally accompanied by parallel shear and slip zones in the mass of diorite overlying, whereby the underlying belts would be carried horizontally forward under and past the overlying belts; and that these would appear as flat faults, of the remarkable kind we find in this Western Cordilleran region. These are called overthrust faults: if my explanation of a certain possible type of flat faults is applicable, some of them may not be overthrust, but undertow, faults. True, overthrust faults may also be due to the shove of an intrusion coming diagonally upward at a flat angle to the surface.

In considering pegmatite veindikes, quartz veindikes and the like, I have called attention to an important consideration which applies to some extent to dikes of igneous rock —that whereas at the time of intrusion of such dikes the telluric pressure of the magma was greater than the incrushing pressure of the fissure walls (which results mainly from the gravity load on the rock constituting these walls), as the process of consolidation of the magma went on, the magma gradually lost its gaseous-tension or telluric pressure, partly through the escape or exclusion on consolidation of volatile elements like water, and partly perhaps from a physical change in the fluid molecules which eventually become the rock-forming minerals; and that as this magmatic pressure relaxed, the walls tended to crowd into

the veindike, as they had before been crowded away from it; and that in soft formations, like schist, under the pressures of great depths this resulted in lenticular veins or strings of lenses instead of the parallel-walled fissure veins which result even under such conditions in rigid rocks. Even in rigid rocks, however, the certain amount of volume which the veindike or igneous dike loses on consolidation results in a diminution of bulk, and the contraction on cooling results in a further diminution, reducing the width of the veindike; and the normally tight and close character of the walls of these veindikes and dikes shows that the walls close in as the dike contracts.

Consider now, along the same lines of thought, a larger irregular intrusion of igneous rock. The loss in volume on consolidation will be considerable, and will call for slight adjustments of the intruded rock throughout, as the rebounding pressure of the walls is felt. As the consolidation of such a considerable intrusive proceeds down and by gradual horizontal tiers or layers from the surface, the shortening due to contraction will be partly horizontal, and in the case of an irregular intrusive the differential shifting necessary will result in many fault fissures of very slight displacement, but with directions of movement into which the horizontal factor largely enters. For example, a regular vertical dike-like band of intrusive rock would cause uniform intrusive pressure on coming in and uniform rebounding pressure from the walls on consolidation—no fault fissures should be developed (Fig. 133). But an irregular bulging out, as seen on a horizontal plan (while the dip of the walls remains vertical), would cause, on intrusion, slight differential horizontal compression of the wall rocks; and on the consolidation of the intrusion, the rebound pressure of the walls should cause similar slight steeply inclined fissures with approximately horizontal differential movement, in the igneous rock and the adjacent walls (Fig. 134). Note the ideal sketches I have made to illustrate this idea: they are made on a horizontal section,

and illustrate the point for a vertical-walled intrusion. But now, instead of a vertical dike, imagine a horizontal sill. If it is of regular thickness, the thrusting upward of its rock

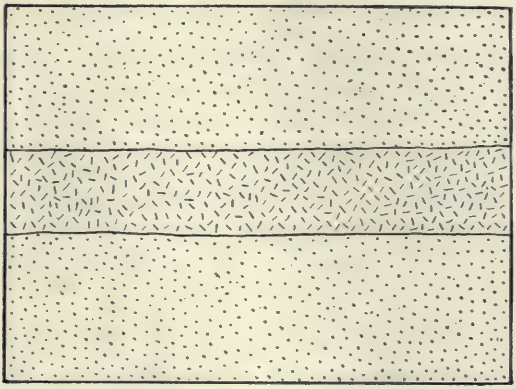


FIG. 133.—Diagram showing lack of fissuring induced by a parallel-walled intrusion.

roof will be even, as will the settling on consolidation of the magma; but if the sill bulges upward into an arch, laccolith or dome, large or small, then the settling back will bring

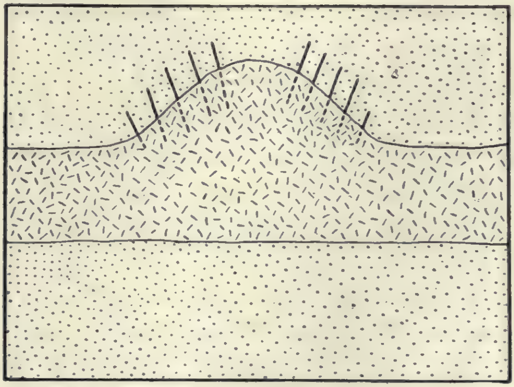


FIG. 134.—Diagram showing fissuring induced by an irregular intrusion.

about slight vertical displacements, and the same two figures as above, conceived as on a vertical plane instead of a horizontal, will serve to illustrate the idea. The section

on a horizontal plane illustrates a likely cause of minor horizontal fault-movements along vertical or steeply dipping fissure planes; that on a vertical plane illustrates a likely cause of minor vertical fault-movements on steeply dipping fissure planes. If the walls of the magma intrusion in question are between horizontal and vertical, slight diagonal fault-movements on fissure planes will accompany consolidation.[17] With a very irregular intrusion, the differential movement adjustments will be quite complex.

Figure 134 taken as a vertical plan suggests a possible new conception of "conjugate" veins. I offer the suggestion for what it is worth; at the worst, I guess that it is better than the old "torsion" explanation.

Viewed in this broad light, nearly all faulting may be due to magma migration—direct or indirect—the direct where the telluric or intrusive or migratory pressure exceeds the restraining pressure of the rock weight, and the indirect which represents the rebound of the gravity pressure (and other rock pressures) when on consolidation and contraction of the intruded igneous mass the telluric pressure diminishes and disappears. The vertical faulting which is due to gravity acting in the rocks above such an intrusion, to adjust shrinkage in the intrusion below; the vertical faulting resulting from the downward drag of the wall rocks when in some cases, as with the volcanic necks at Tonopah, the volcanic plug sags after hardening; the horizontal faulting which takes place on the steep sides of an intrusion, to adjust its horizontal shrinkage on consolidation by that side-thrust from the walls which is the gravity pressure transmitted tangentially; the oblique faulting which represents various combinations of the above cases: all these come under the head of indirect magmatic faulting, or "intrusion-rebound" faulting or "adjustment" faulting.

This condition of veins occupying steep fissures of slight displacement where the differential movement has been

[17] Compare Butler's figure (*Econ. Geol.*, Vol. X, 1915, p. 119), which shows the same idea on the vertical plane. This paper is an important one.

in a persistent horizontal direction, is a very common and striking one, and one which must be of prime importance in diagnosing the nature and origin of fissure veins, as I have done above. So far as I know, the work done at Georgetown by myself and associates first called special attention to this common phenomenon. In the Silver Plume district, at Georgetown, which is a silver-lead-zinc district, in dozens of veins (all steeply dipping) which were noted, the majority of the striæ on the walls (which striæ record the direction of movement) are horizontal or dip at angles ranging only up to 5°.[18] In the adjacent and contiguous Idaho Springs district the auriferous pyrite veins occupy fissures of slight displacement, of strike and dip similar to those of the Silver Plume (Georgetown) region, but the striæ record the fact that the differential movement was quite other than at Silver Plume, being steep, up to vertical, and averaging perhaps 60° to the southwest, on the usually northeasterly striking veins (Fig. 135).[19] The very distinct types of ores in these two contiguous districts are associated with different igneous rocks: the Georgetown silver-lead-zinc veins with various dikes of the alaskite-monzonite group, and the Idaho Springs gold-pyrite veins with dikes of the alkali-syenite group.

Before drawing further conclusions, I will add to my data the work of Bastin (*Professional Paper* 94, U. S. Geol. Surv., 1917), published nine years after my Georgetown report. Bastin's work was on a continuation of the Silver Plume-Idaho Springs ore zone that I and my associates had studied, the areas of the two investigations being separated by an arbitrary line. His work carried him on, northerly, along the great continuous mineral belt of Colorado, through the Idaho Springs and Central City region, and on north into the southern part of Boulder County. It is all, from Silver Plume to Boulder County, part of one great mineral district. Bastin found in this area the same

[18] *Professional Paper* 63, U. S. Geol. Surv., p. 167.

[19] *Op. cit.*, p 162.

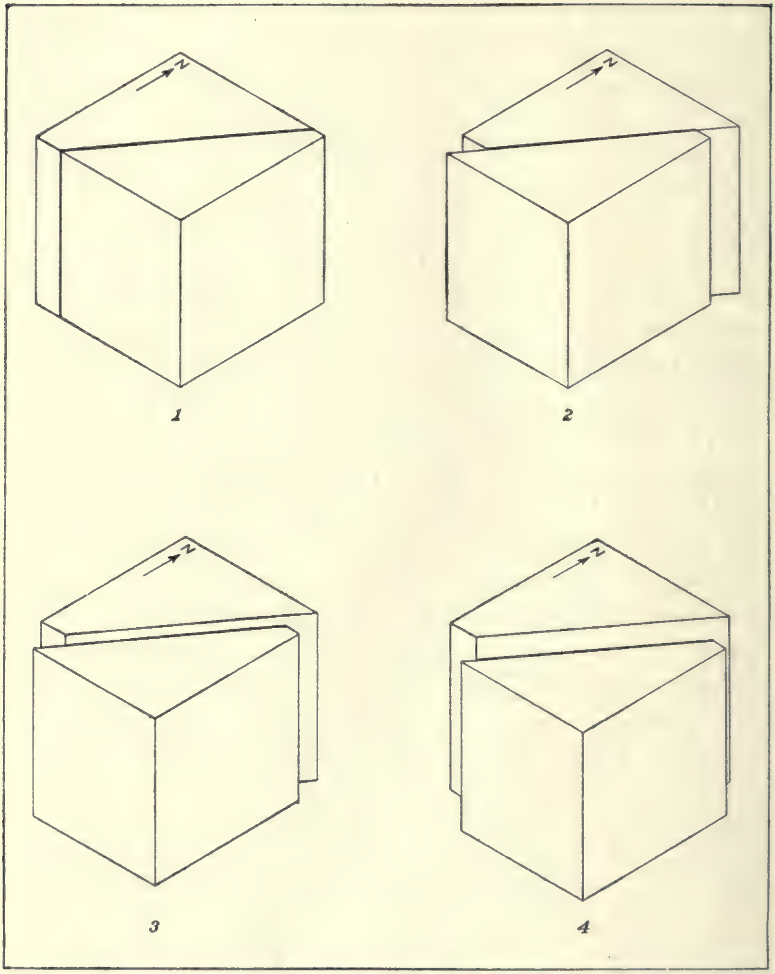


FIG. 135.—Stereogram of average fault movements in the Georgetown quadrangle. These figures show the nature of the displacement along slight fault fissures which have later become veins. 1, Unfaulted block of rock (upper side horizontal) with vertical northeast fracture running through it; 2, horizontal displacement along fracture shown in 1, illustrating general type of movement in silver-bearing veins belonging to the Georgetown group; 3, movement at an angle of about 20° from the horizontal, illustrating displacement along the Colorado Central mine vein-fissures; 4, movement at an angle of 60° or so from the horizontal, illustrating typical displacement along the fissures of auriferous veins of the Idaho Springs type. After Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 29.

division into gold-bearing pyritic veins and principally silver-bearing galena-blende veins as I did on my side of the fence. In the first type the predominating sulphide is pyrite, with subordinate chalcopyrite (the ore averages less than 1.5 per cent metallic copper, though in some rich shipments it has risen to 17 per cent); also common tennantite (copper sulpharsenide), and in a few veins enargite (iron-copper arsenide). "Gold greatly predominates in value over the other metals."[20] The predominant gangue is quartz. In the second type the principal sulphides are sphalerite and galena, with some tennantite and less chalcopyrite. "In general, the primary ores of the galena-sphalerite type are poorer in gold and copper and richer in silver than those of the pyritic type."[21] Besides the predominant quartz as a gangue mineral, carbonates (siderite, calcite, rhodochrosite) and barite are abundant.

These are the same two types which I described, though the galena-blende veins are not quite so clean-cut and pure a type as at Silver Plume. Bastin found these two types of distinct age, filling fissures created at different periods, and, as I described, often occupying successively the same successively reopened fissures, to form mechanically integrated or "compound" veins.[22] From rather scanty evidence, I thought that the gold-pyrite veins were the younger. Bastin found a great deal of evidence which indicates that they are older. I believe he is right, and it clears up the situation. The veins which I found younger than the galena-blende veins in the district I examined were siderite-pyrite veins and pyritiferous quartz veins, very low grade with respect to precious metals. I correlated these, with some hesitation, with the pyritiferous gold vein type; but I now abandon that correlation, and recognize them for what they evidently are—the barren-gangue veins, containing, however, in the cases I

[20] E. S. Bastin: *Professional Paper* 94, U. S. Geol. Surv., p. 105.
[21] *Op. cit.*, pp. 110-112.
[22] Spurr and Garrey: *Professional Paper* 63, U. S. Geol. Surv., p. 135.

saw, enough pyrite to make it confusing. The presence of abundant arsenic locally in the form of enargite in the Idaho Springs–Central City region also helps in the diagnosis, as does also the occurrence in these veins of rare molybdenite. Taking it altogether, we have then, in this whole region, in the natural sequence: 1 (Molybdenum),[23] gold, arsenic, copper; 2, zinc, lead, silver; 3, quartz and mixed carbonates (lime, manganese, iron, magnesia). The first two stages represent the normal magma-sulphide stages; the last, the barren-gangue magma stage. In each of the first two stages there is very little orderly sequence of mineral deposition; each, therefore, represents a telescoped sequence; but the hiatus in the center of the sulphide ore sequence, produced by separate injection, and the marked division of vein types, renders this a valuable and instructive example. The third or barren-gangue stage, scantily represented, was also not noted as showing the usual clean-cut internal sequences. There is here, then, the whole magmatic vein sequence characteristic of falling temperature, divided artificially by some magmatic accident, or by two magmatic accidents, into three groups, but each telescoped upon itself so as to indicate rapid consolidation and hence superficial conditions of consolidation.

The two chief sulphide-ore vein types are more mixed geographically in the Idaho Springs–Central City region than in that between Silver Plume and Idaho Springs, but are still segregated in large part. The Idaho Springs Quadrangle Map[24] shows a decided areal segregation of the two types, as does the Central City special map.[25] The connection of the pyritic ores with the alkali-syenite magma dikes and that of the lead-zinc veins with the monzonite magma dikes is not so clearly shown in the region mapped by Bastin as in the Silver Plume–Idaho Springs region, though it is roughly but unmistakably indicated in his

[23] Molybdenite was the first mineral to crystallize.

[24] Bastin: *Professional Paper* 94, U. S. Geol. Surv., Plate VII.

[25] *Op. cit.*, Plate IV.

Idaho Springs Quadrangle map; but the association becomes still further obscured and indeed quite lost in the Central City map.[26]

Let us first consider the monzonite (quartz-monzonite) porphyry intrusion. This represents essentially an undifferentiated magma type, because it is found in great quantity throughout this whole Colorado belt of igneous rocks. It occurs as abundant and extensive dikes—and also as irregularly circular, or irregularly elongated, pipes or stocks, the nearly circular ones, as at Empire, having a diameter up to nearly two miles; the elongated ones, as near Tolland,[27] having a length up to two and a half miles and a width of a mile or so (Fig. 136). Inspection of Bastin's maps brings out one instructive lesson: although the monzonite porphyry dikes are intimately associated with the veins, and immediately preceded them, the veins certainly do not seek those places where the monzonite is most abundantly represented. The most intense zone of veining, perhaps, in the district (that which runs, curving, east-northeast to northeast through Central City) is remarkable for the small number of its dikes, and those are of the alkali-syenite (bostonite) magma. The larger intrusions of monzonite increase in frequency and size toward the north of the area mapped—and I observe that the number of veins falls off as if correspondingly; moreover, that the maps show that the veins tend very markedly to avoid the larger monzonite stocks and their immediate vicinity. All this clearly points to the fact that at the period of ore deposition the vicinity of the large masses of intrusive monzonite were at a temperature too high for ore-magma consolidation, which took place mainly at a certain zone above, and quite rapidly, and all within a certain restricted vertical range, as is the manner with "telescoped" veins. The great number of systematic slight fault fissures which became the seat of

[26] *Op. cit.,* Plates III, IV.

[27] *Op. cit.,* Plate I.

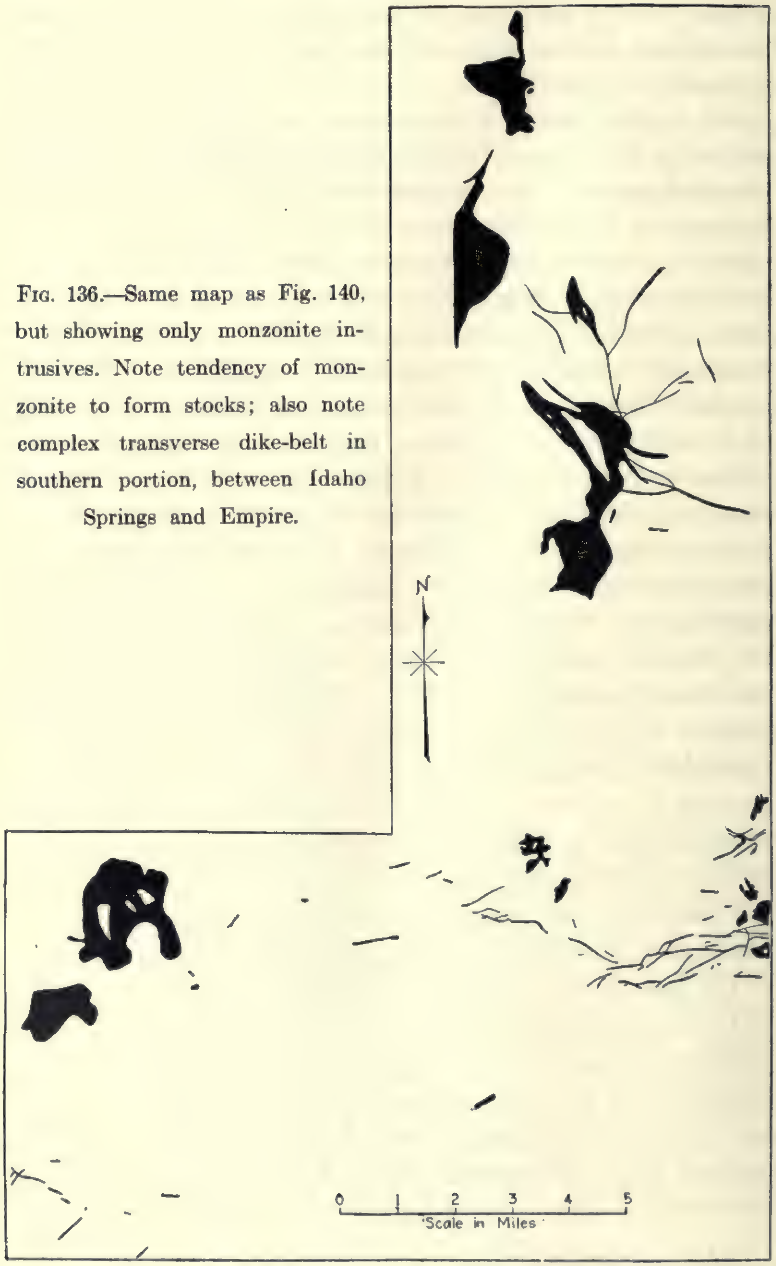


FIG. 136.—Same map as Fig. 140, but showing only monzonite intrusives. Note tendency of monzonite to form stocks; also note complex transverse dike-belt in southern portion, between Idaho Springs and Empire.

this ore consolidation were formed soon after the first consolidation of the intrusive magma: the veins traverse the monzonite dikes, although some of the later dikes, as the biotite latite dike at the Stanley mine,[28] are later than the veins. At the Stanley mine a bostonite dike is also earlier than the vein, and all three—the two dikes and the vein—were successively injected along the same fissure. Here we have one of the frequent cases of a subordinate last dike phase being later than the vein periods, showing repeatedly how definite a magmatic episode is ore deposition in these cases, and how clearly the ore solutions were an ore magma. Bastin[29] observed in the case of the Blue Bird vein, some 15 miles away from the Stanley, along the ore belt in a north-northeast direction, that a dike of biotite andesite porphyry cuts a fissure vein of the galena-blende type.

The Stanley vein contains mainly quartz, pyrite, and considerable galena and chalcopyrite, and a little siderite. I grouped it with the "Idaho Springs type of gold-bearing veins" on account of its gold content and its chiefly pyritic filling, with chalcopyrite. I note that Bastin and Hill[30] group it as a "gold-silver vein of galena-sphalerite type." Reviewing the subject, I think it very safe to classify it as a composite or compound vein representing a merger of both types—whether marked by an intermediate fissuring and recementation I cannot say, though from the uniform history of the district, it would be altogether likely. We would have, then: 1, Bostonite dike intrusion; 2, vein intrusion—all three stages; 3, biotite latite intrusion; all along the same fissure.

As the principal stock and dike types—monzonite and bostonite—are always older than the ore of all these districts, we have in general: 1, Main stock and dike intrusion, in various stages; 2, vein intrusion in various stages; 3,

[28] J. E. Spurr: *Professional Paper* 63, U. S. Geol. Surv., p. 344.
[29] *Professional Paper* 94, U. S. Geol. Surv., p. 185.
[30] *Op. cit.*, Plate VII.

minor dike intrusion in various stages.[31] Now, between the pre-ore dikes and the post-ore dikes there are close magmatic relations: the pre-ore bostonite and the post-ore biotite latite each contain a very large excess of potash over soda. The biotite andesite porphyry dike which cuts the galena-blende stage vein near Nederland (p. 759) belongs to a series of dikes considered by Bastin and Hill to be differentiation products from the monzonite magma.[32] Therefore, the whole process of ore deposition, or, better, vein injection, in all its stages, took place as an episode, within the period of differentiation of the main intrusive monzonitic magma; and the ore magma (which was itself subject to the characteristic minor differentiation into stages) was one of the differentiation magmas.

Interesting further evidence of rock differentiation is given by Bastin and Hill. In the northern end of the area mapped (but not yet the end of the ore-and-intrusion belt), at Caribou Hill, there is an intrusive stock of monzonite, within which are irregular bodies of gabbro and pyroxenite, which represent differentiation phases of the monzonite magma, and within these bodies are irregular bodies of iron ore (magnetite and titanite) which are a further differentiation, and are believed to be in part differentiations in place.[33] The iron ore as illustrated by Bastin and Hill contains in its lean stages much intercrystallized pyroxene (augite), and it is interesting to note that the magnetite incloses fairly well-shaped augite crystals, suggesting that it is later than the augite (see p. 561).[34]

[31] Certainly both biotite latite and biotite andesite, as above; also, perhaps, alkali syenite porphyry (*Professional Paper* 63, U. S. Geol. Surv., p. 135).

[32] *Professional Paper* 94, U. S. Geol. Surv., p. 51.

[33] *Op. cit.*, p. 48.

[34] The occurrence of a tungsten-ore district in this same belt of Tertiary intrusion and ore deposition (may I coin the word *magmatism* for the whole scope of phenomena?) will doubtless afford further instructive lessons when carefully studied. The data available at present are not sufficient to warrant introducing the tungsten into the discussion; but *a priori* there is little doubt that it represents simply a high-temperature phase of the Tertiary ore deposition.

Finally, we have the unique case of the Evergreen ore deposit, which occurs about half way between the Caribou titaniferous iron ores and Idaho Springs, which are about 15 miles apart along the ore zone. So far as I know, there is no other existing ore deposit like the Evergreen. It was first described by Ritter,[35] who showed that the ore deposit was a dike rock in which the copper sulphides crystallized contemporaneously with the silicate minerals. The Evergreen dikes are intruded in pre-Cambrian schist and pegmatite: they are fresh and of granular texture, consisting mainly of potash feldspar (orthoclase and microcline), augite, quartz, and wollastonite, with some titanite, garnet, zircon, and calcite, and a little magnetite, all primary and original minerals. Only locally chalcopyrite and bornite occur "in small and very irregular patches"; and are associated with abundant garnet, and also with augite, wollastonite, and quartz. All these minerals are part of the fresh rock fabric. Monzonite dikes near the mine consist of predominant orthoclase and augite; and a dike which is "probably a continuation of the ore-bearing dike is similar in every way to the dike rock of the mine except for the absence of sulphides, garnet, and wollastonite." Bastin and Hill[36] consider four hypotheses of origin for this ore: 1, Magmatic differentiation alone; 2, absorption of materials necessary to form copper sulphides and other extraordinary minerals from the immediate wall rocks; 3, same as No. 2, but absorption assumed only from wall rocks or veins in depth; 4, combination of magmatic differentiation and digestion of wall rock. Of these hypotheses the writers prefer No. 4, concluding that the "dike is strongly suggestive of digestion of calcareous wall rock, wollastonite in particular never having been described as occurring so abundantly in rocks of purely magmatic origin. Such digestion of material probably took place before the rock reached its present position. The sulphides may have been

[35] E. A. Ritter, *Trans.* A. I. M. E., Vol. XXXVIII, 1908, pp. 751-765.
[36] Bastin and Hill: *Professional Paper* 94, U. S. Geol. Surv., p. 127.

derived either from the wall rocks through absorption, or from the magma by magmatic differentiation. The deposit under this view represents an endomorphic effect produced by contact metamorphism at the border of a large intrusion of monzonite."[87]

Unique ore deposits are due to unique causes; they represent accidents, not normal processes, as I have remarked in the case of the New Jersey zinc oxide deposits. The Evergreen ore is, I should say, not due to magmatic differentiation—if so we should have other examples, as we do so abundantly in the case of magnetite, ilmenite, chromite, etc. All real cases of magmatic differentiation represent rules, not exceptions. Aside from these general but reliable considerations, the local evidence indicates the same conclusion. The ores are very irregularly bunched local inclusions in an otherwise normal augite monzonite dike—not inclusions in the ordinary sense, because they are of simultaneous crystallization with the ordinary dike minerals, but inclusions in the magmatic sense—pre-consolidation inclusions. These inclusions represented copper sulphides, quartz, and calcite, the two latter of which magmatic elements have crystallized in part as lime silicate (wollastonite). The local and bunchy nature of these inclusions indicates that they were locally acquired. Through absorption from the wall rocks or from digestion of the wall rocks? Nothing more improbable—these dikes always cut the wall rocks without penetration or absorption: that they should have extracted these certain elements, especially a notable quantity of copper, from the ordinary rocks they penetrated, is quite out of the question. Therefore, I rule out the "digestion of calcareous wall rock"; besides, this occurrence is in the schists and pegmatites, and there are no calcareous wall rocks to be found in depth. There was, then, a local source—an addition or inclusion, by one of the accidents of intrusion, of concentrated copper sulphides, quartz, and calcite. An already-formed vein, then, a vein of copper

[87] *Op. cit.*, p. 129.

sulphides, quartz, and calcite? Near the truth, but I do not think it likely. The biotite latite of the Stanley mine cuts the sulphide veins sharply without other than very slight absorption: there have been many cases reported of igneous dikes cutting sulphide veins, but never a case of important digestion and recrystallization. Therefore, I fall back on the conclusion that the copper sulphide–quartz–calcite accession was that of an ore magma, and that the monzonite magma and the ore magma, traveling different roads, met, and the former (the more copious one) captured the latter and both became mixed locally to form that unique and strange thing, a composite or compound rock-ore magma. Lime characterizes these ore magmas, as we have seen, though they are derived from igneous magmas; the materials that have been added to the monzonite magma represent the typical copper-sulphide ore magma. I have shown (p. 666) how ore magmas of different types representing different substages of differentiation, traveling different roads along different fissures, meet, as in the Eden mine, and in the Tecolotes mine, to form a mixed ore magma, which crystallizes, of course, simultaneously. In the case of the Stanley mine, where we have in rapid succession one potassic dike injection, an ore-magma injection, and another potassic dike injection—how much more of a coincidence would it have been for our ore magma, unsolidified, to have met one or the other of the dike magmas, unsolidified, and mingled with it? So little of a further coincidence that I fancy we may find, here and there in the world, other isolated cases of the mingling of ore magma and rock magma, like that of the Evergreen mine. But note that the Evergreen mine, even in its own district, is not a type—it is a coincidence, a happening, an accident.

The occurrence of a single type of igneous rock, in scores of different dikes in this region we are discussing, points to their having been sent up from a common body below, of which these dikes are only the up-reaching tentacles. As to the size of this mother intrusive magma at greater depth,

it must at least be as long and as wide as the belt or zone of dikes, which reaches up northeasterly across central Colorado.[38]

Concerning the dikes, which are associated with the ores, but never so closely as to warrant any conclusion of closer genetic relation than that both came from the same common source in general—the underlying magma reservoir: in general, dikes and veins certainly follow the same fissure sets or systems. Sometimes, as has been explained, dikes and veins successively occupy the same fissures, which is also a common phenomenon in many other mining districts; but in general they are independent. Different periods of dike intrusion also follow as a rule different fissures, just as the different vein types—meaning the pyritic gold type and the silver-lead type—in general follow different fissures. The Idaho Springs and Central City special maps of Bastin and Hill [39] make up a good chart for studying these things. They show two chief types of dikes —monzonite and bostonite; and the two chief types of veins above mentioned. All these follow the same general laws of trend. There is a predominant northeasterly set, swinging about, as to exact trend, pretty widely in different areas, and a marked but quite subordinate essentially northwesterly set.

Each of these four typical classes of intrusions—two of dike rocks and two of ore veins—tends to occupy predominantly independent areas, though in some areas they mingle. Yet the parallelism of their trends remains pretty faithfully concordant; and in different areas, where the general trend of the northeast dikes (for example) curves from east-northeast, to northeast, as it does in the Central City district, this areal change of trend is participated in fraternally by all dikes and all veins. Now, the dikes, like the veins, occupy fault fissures of very slight displacement.

I note one monzonite dike in the Idaho Springs Quad-

[38] *Professional Paper* 63, U. S. Geol. Surv., Plate XI.
[39] *Professional Paper* 94, U. S. Geol. Surv., Plates III, IV, VI, VII.

rangle map which offsets a pre-Cambrian contact some 250 feet horizontally, showing the fault nature of the dike fissures, but this is quite unusual, and in nearly every case the dike fissure crosses such contacts without faulting sufficient for mapping. In this respect the dike fissures are identical in character with the vein fissures. The cases where veins and dikes have successively occupied the same fissures show further the similarity of the dynamic causes which produced the fissuring preparing for and guiding the intrusion. Not only this, but the slight faulting, which is later than all veins and dikes, is of the same description.[40] The greatest observed amount of faulting of a dike amounted to 200 feet horizontally, in the Silver Plume district.[41] This figure, like the one given above, however, is quite exceptional. The special maps of the Idaho Springs and Central City districts, by Bastin and Hill, and of the Silver Plume district, by myself and Garrey, together with the studies thereon, afford the best data I know of, anywhere, for studying this subject, because the very large number of irregular contacts of the pre-Cambrian formations, across which the Tertiary fissures cut, and which have been carefully mapped, proves fully the nature of all these fissures—namely, that, whether dike fissures, vein fissures, or unfilled fissures, they are straight, long, steeply dipping, frequently branching faults of very slight displacement. Indeed, the dikes have the same "linked" habit as the veins (Fig. 137 and Fig. 138), characteristic, as I have pointed out in the case of veins, of fissures of slight differential movement, and apparently typical of conditions of light load, relatively not very remote from the surface—although the reason for this last qualification, if true, I do not know.

The above characteristics of dike fissures, vein fissures, and empty fissures show that they all obey the same physical laws, and all are due to the same cause which has

[40] SPURR and GARREY: *Professional Paper* 63, U. S. Geol. Surv., p. 107, Plate XXI.

[41] *Op. cit.*, Plate XXI.

operated during the Tertiary for a considerable period, and which is fairly constant in special areas, which, however, retain an individuality as compared with contiguous areas in the same magmatic belt. Taking the general direction of all—northeast—it seems clear, as I long ago pointed out, that this conforms to the general direction of the central

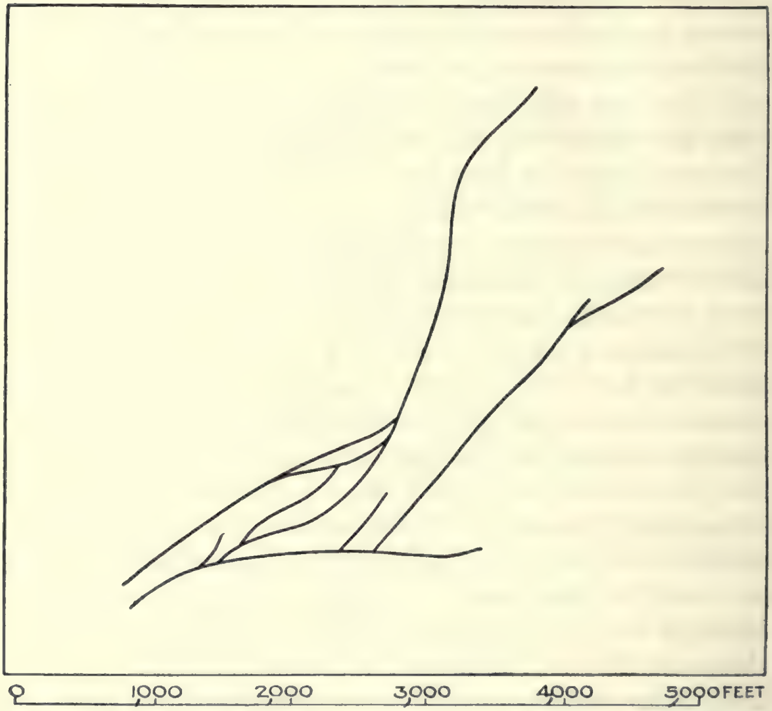


FIG. 137.—Central City district, Colorado. Detail of Tertiary dikes (monzonite) intrusive into pre-Cambrian complex, showing branching and semi-linked habit. From map of Bastin and Hill.

Colorado intrusion-and-ore belt; and, moreover, that the northwest trend is transverse to or across the belt. These trends vary a great deal; but then the outline of the belt is irregular, and varies a great deal; but I believe that the dominant laws of strain are shown to be in general mainly parallel with the general trend of the magmatic belt and transverse to it, as, on a much smaller scale, at Matehuala;

and that, therefore, the fissures are, similarly, contraction-adjustment fissures, due to the progressive consolidation of the magma beneath. I could adduce a great deal of detailed evidence from these maps to support this conclusion, but I cannot take space to make the discussion complete; I will mention only one or two points. The bostonite

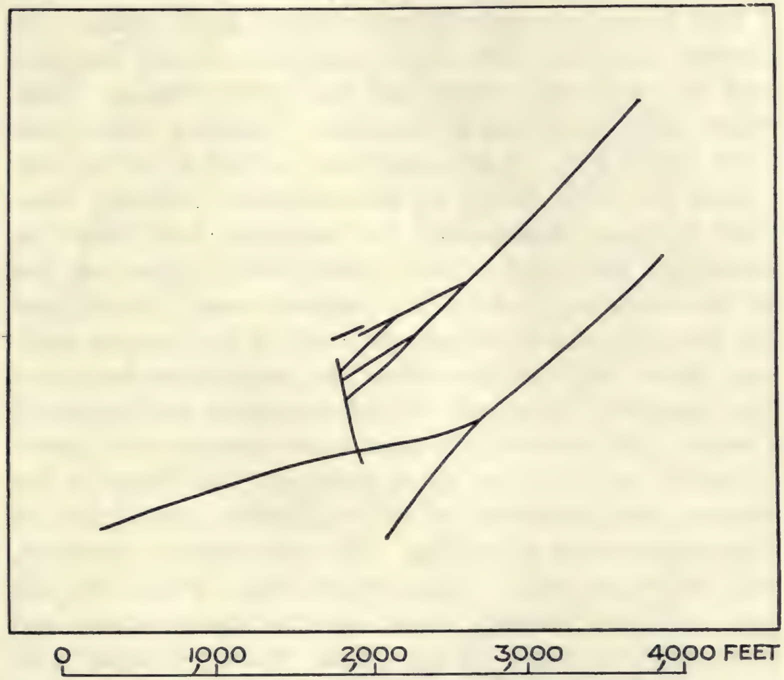


FIG. 138.—Central City, Colorado. Detail of Tertiary mineral veins, showing branching and semi-linked habit. From map of Bastin and Hill.

dikes in the Idaho Springs–Central City region are characteristic of an area which represents the field or angle of a change in trend of the whole ore belt, from northeast (to the south of here) to north-northeast (north of here). Also, this angle is the site of the greatest ore deposition, and the greatest number of veins, comprising as it does the Silver Plume, Idaho Springs, and Central City areas, of which the fissures of the last two span this elbow of the belt. The

nearly east-west trend of the vein belt of Silver Plume[42] corresponds with the straight easterly shoot of the southeastern boundary of the magmatic belt south of the Idaho Springs region (Fig. 141).

In Fig. 139, I show the main bostonite dikes. I should like to show the veins also, but should have to generalize too much to make the figure intelligible; but the veins, as I said, follow the same fissure systems as the dikes. On another map (Fig. 140), I have included both the bostonite and the monzonite dikes and the other Tertiary dikes. These show the strongest direction of fissuring to be transverse to the belt. In the same map, as well as in Fig. 136, I show the stocks, which are all monzonitic. As seen, these tend to trend parallel with the magmatic belt, while the associated dikes tend to trend transversely to the belt and to the elongated stocks. This makes it clear, I think, that the line of stocks represents the trend of the magma reservoir below, and that the stocks are protuberant humps of that reservoir; as, indeed, the differentiation phenomena of Caribou Hill (the northernmost stock shown on the figure) indicate; but that the dikes represent the filling of the fissures that originated by the contraction adjustment of this magma mass in cooling. The vein fissures, therefore, have the same origin. Veins which cross Caribou Hill run east and west, like the dikes; and the great number and complexity of dikes in the Idaho Springs–Central City region, too great for representation without generalization on this scale, is accompanied by a corresponding but still greater complexity and number of veins in these districts. All these veins are, therefore, "domestic" veins, and indeed the dikes are "domestic" dikes.

The monzonitic dikes in this region were perhaps the earliest of the fissure fillings. Little different in general character from the magma of the stocks, they represent a stage of slight differentiation of the intrusive and consolidating magma body beneath this belt. The later bos-

[42] Spurr and Garrey: *Professional Paper* 63, U. S. Geol. Surv., Plate XXI.

FIG. 139.—Same map as portion of Fig. 140, but showing only bostonite dikes. As compared with monzonite, note lack of stocks; note restricted areal occurrence of bostonite. Note, also, two types of habit of occurrence—first the northern area of extraordinarily long dikes, predominantly transverse to the ore belt; second, the area of predominantly short dikes south of Idaho Springs.

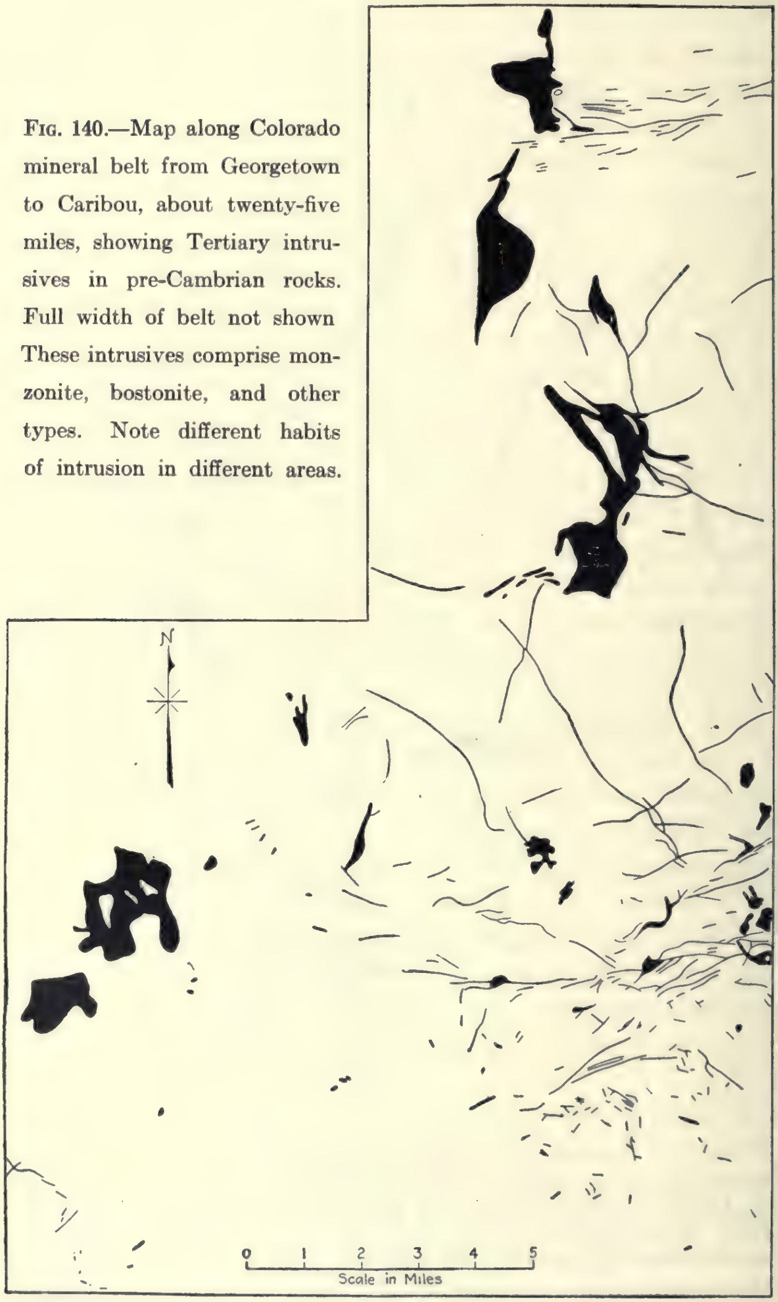


FIG. 140.—Map along Colorado mineral belt from Georgetown to Caribou, about twenty-five miles, showing Tertiary intrusives in pre-Cambrian rocks. Full width of belt not shown These intrusives comprise monzonite, bostonite, and other types. Note different habits of intrusion in different areas.

tonite dikes represent a more highly specialized magma, and register the further progress of differentiation beneath. Then come up the ore magmas—first a telescoped or mixed magma of the higher-temperature zones—copper-gold-arsenic chiefly; then, after the sealing of the fissures by this, rest; then a jar or jolt throughout the belt, and resplitting of fissures; and then the injection of a telescoped or mixed ore magma of the zinc-lead-silver metals, chiefly—of the lower-temperature ore zones. The telescoping at each ore episode represents and signifies both a shallow underlying magma, and a vein horizon near the surface, with a rapid decrease of temperature upward; therefore, a limited total vertical zone of ore deposition, such as is characteristic of all the Tertiary veins.

According to my theory and belief, when the veins of the gold-pyrite type were being formed, veins of the silver-lead type were being formed above, in an upper rock region, now eroded off: their superposition afterward, on the higher-temperature veins, by migrating downward with falling temperature (due to the downward progress of cooling of the magma below) is quite the rule. Finally, after the ore deposition, came other, but sparse, dikes, the laggards of the dike series—showing that the vein sequence of ore deposition, "from soup to nuts," is a prompt and specific magmatic differentiation feature, as compared with the whole range of dike after-injection (see p. 360).

The indications are that the underlying magma reservoir came closest to the surface at the northeast end of the area mapped, as is shown at this end by the monzonite stocks showing differentiation, as well as by the titanium, tungsten, and copper ores (signifying high-temperature conditions) in this section.

The horizontal movement of the Silver Plume vein-fissure faulting indicates lateral adjustment due to differential horizontal shrinkage on consolidation of the magma body beneath. This, according to the rules I attempted to formulate (p. 750), indicates a horizontal bulge or irregu-

larity in the belt; and this corresponds with the actual conditions. The horizontal differential thrust along the line A. B. (Fig. 141) was continued into the magma belt and represents the Silver Plume vein-fissure zone c. d. This was accomplished by and during consolidation, as shown by the vein fissures being later than the Silver Plume quartz monzonite porphyry dike; it is a case of horizontal

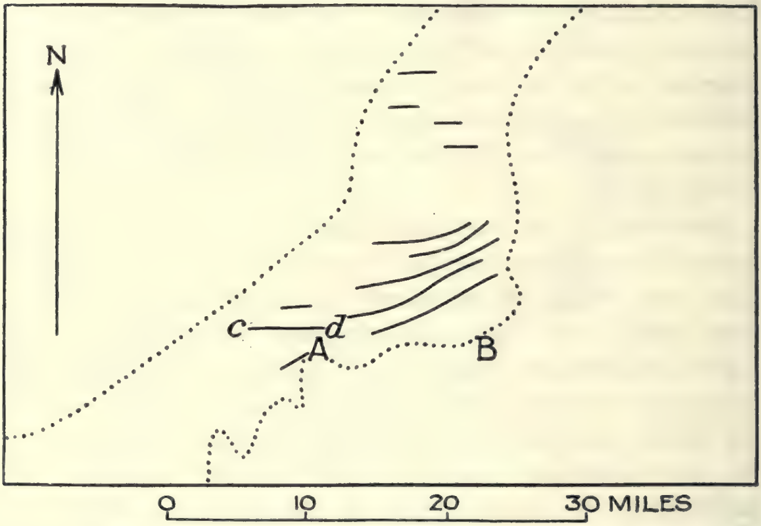


Fig. 141.—Diagram of portion of Colorado ore belt, from south of Silver Plume northeastward to Caribou. Area within dotted lines is belt of intrusive Tertiary porphyries. Solid lines show general trend of mineral veins, from Silver Plume on south to Caribou on north. For further explanation, see text. Data from maps by Ball, Spurr and Garrey; Bastin and Hill.

adjustment fault-fissuring. The slight magnitude but wide distribution of these little fault fissures at Silver Plume and elsewhere in the belt indicate the cause I have assigned as the correct one. Where the vertical component of faulting is larger, as near Idaho Springs (p. 754), then the vertical element of consolidating magma adjustment enters as a factor, and the relative importance of these two forces determines the actual angle of fault movement in each case, while faulting in the direction of the dip indicates simply

sagging of the magma below, or vertical adjustment fault-fissuring.

The dip of the veins in this district follows the rule for fissure veins, being predominantly at angles of 60 or 70°. This applies to different sections, regardless of change of strike. This seems to me to indicate that the origin of these fissures is in a vertically exerted force, regardless of the direction in which subsequent adjustments were made along these planes, which adjustments will be recorded in the striæ. This vertical force may be the result of the underlying magma surgence, or of its subsequent sagging, or both. The average angle of 60 to 70° is the average angle not only for the veins of this belt but for all fissure veins as well.

One general trend of vein fissures of slight or no displacement, then, coincides with the long axis of the underlying magma intrusion; and another set at right angles corresponds with the short axis. The general east-west trend of veins in Western North America, as I have advanced elsewhere (p. 479), may indicate an easterly-westerly trend of subcrustal magma invasions.

As for the dips, these may be in either direction. When the two directions appear in a given region, they have been called conjugated veins. Note that conjugated veins may dip away from one another, or toward one another. At Grass Valley, California, Lindgren has shown, on either side of a granodiorite intrusion into porphyrite and diabase, and especially in both intruded and intrusive rocks for a broad zone near both contacts, a major system of conjugated veins dipping at an angle of 45° or less toward the intrusion. This indicates identical stresses on both sides of the granodiorite intrusion, and I, therefore, refer the stresses to the granodiorite. A sagging of the granodiorite after intrusion is, I think, indicated (Fig. 142).

The cross section of Lindgren shows, in addition to the major system of conjugated veins dipping, in the general vicinity of both contacts of the intrusive granodiorite,

toward the granodiorite: also a minor system of conjugated fissures, similarly located in general in regard to the vicinity of the intrusive contacts, which dip away from the intrusives, on both sides, at angles similar to those of the major system. I do not know if this section, which I reproduce, is safe to reason from, without further knowledge: but with such knowledge as I have, I suggest that the minor system represents the strain of the rising or surgence of the igneous intrusion during and after consolidation, and the major system its subsequent sagging.

A simple case of conjugated veins dipping away from an igneous intrusion, and due, as already reasoned out, to the surgence or continued uplift of a volcanic plug after

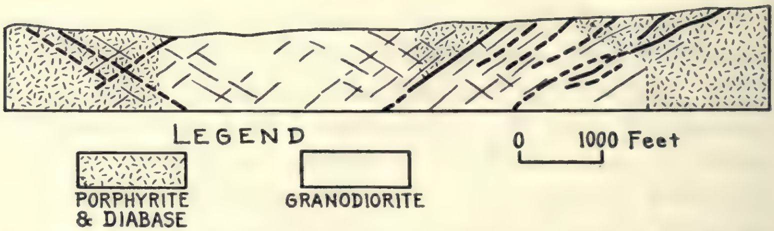


FIG. 142.—Conjugated veins, Grass Valley, California. After W. Lindgren: U. S. Geol. Surv.

consolidation, is described earlier in these essays (p. 278) at Tepezala. The fissures which have been filled to form these veins are fault fissures, due to direct vertical intrusion-faulting.

At the Golden Star mine, at Kofa, Yuma County, Arizona, where I spent some time in an examination in 1909, the vein follows a heavy fault (Fig. 143), and, therefore, an analysis of the geologic history may well be of interest.

This Western desert country is wonderfully interesting geologically, and has been frequently abused and treated superficially by geologists, riding on the Sunset Limited through its ranges; or consulting the literature and their own inner convictions in the East. The Golden Star vein lies at the foot of a bold, straight mountain scarp which

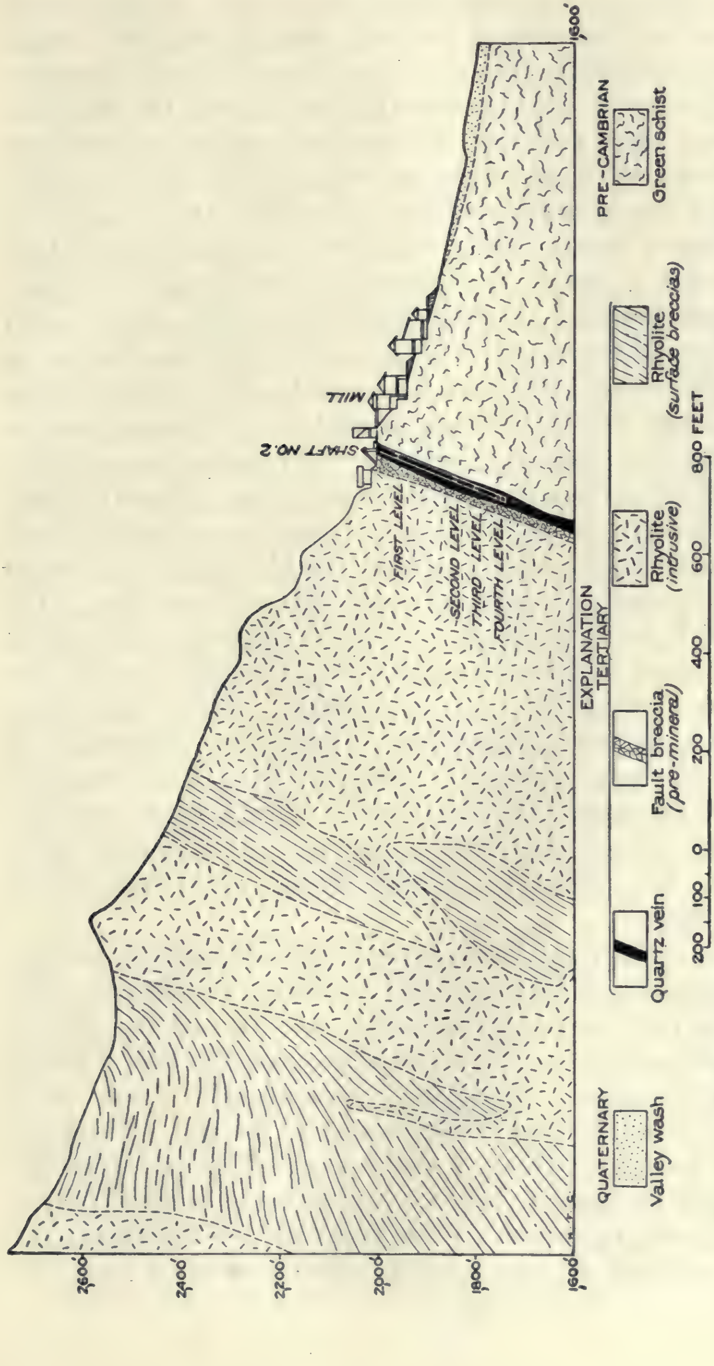


FIG. 143.—Kofa, Yuma County, Arizona. Vertical cross-section of Golden Star mine. See text. By J. E. Spurr.

rises from the low-lying desert at its base. Is there, then, a fault at the base of the bold straight mountain scarp? There is, indeed. Then the mountain is a block mountain, and owes its relief to faulting? You may call the mountain by any name you wish, so long as you retain an intelligent outlook, and do not lapse into subjectivity; but the mountain is the downthrown block. The plain at its base is the upthrown block. Then why is the mountain a mountain, and not a valley, or "graben" if you please? Erosion, erosion, erosion! Differential erosion, which washes away soft rocks more swiftly than hard. The mountain is of rhyolite—hard; the plain is of schist—soft. When erosion had excavated to a certain general level, it found rhyolite on one side, schist on the other. Did erosion care whether the rhyolite was a downthrown block or an upthrown block? It did not. If the rhyolite had been an upthrown block instead of a downthrown block, would it still have formed a mountain? Certainly it would, just as it now does. The present front is along a *reversed erosion fault scarp*. The desert is full of simple things like this, but not yet simple enough for many a geologist. Then the erosion must have been tremendous? It has been—thousands of feet of rocks, measured vertically, have been removed. Then the range has developed a "mature topography," "broad valleys" and other indications of "advanced age"? It has not: forget it. Things do not work that way in the desert.

The oldest rocks here are pre-Cambrian schists—like the Pinal schists at Ray (p. 224): a complex of primeval sediments, injected by igneous rocks—granitic and the like, all sheared and flowed out under great pressure, then injected again by granitic rocks, then tremendously, deeply worn away, exposing their depths finally to the sun. There are some interesting things I could decipher for you from this stupendous history—but it is not germane to what I especially want to discuss. These rocks are pre-Cambrian. As the novelists say, let us skip without mention some six

hundred million years, according to the best geological time scale,[43] and we have skipped the record of all known geological life down to the Tertiary, the Age of Mammals, and, toward its close, also of Man. There were, as you know, great volcanic outbursts in the Tertiary: and some of them happened here—happened when the surface of this part of Arizona was entirely of these pre-Cambrian-complex, sheared-and-flowed rocks. Here, in the district I am discussing, there came a rapid succession of explosive outbursts, recorded by layered breccias, and also rhyolite flows, all piled upon one another for some thousands of feet along certain lines of eruption. Afterward, sagging, collapse—and the piled-up lavas sank, breaking down the superficial crust, making downthrown fault blocks, letting the heaviest weight of lava-rock accumulations sink back into the crust, past the better (because more age-long) adjusted schist areas, less heavily volcanically weighted by this Tertiary catastrophe. One of the principal faults delimiting these blocks lies where now is the Golden Star mine, owned at the time of my examination by New York capitalists. The lava beds are crumpled and dragged up along the fault, and for a broad neighboring zone; there is a thick fault breccia; the fault breccia is fairly straight, and long; the volcanic accumulations form the mountain, and the schist forms the plain; the fault dips into the mountain at the usual angle of about 70°, as shown in the cross-section (Fig. 143); and (geologists, thank the miners!) the mine workings have explored the fault on the strike and several hundred feet in depth. The amount of vertical differential movement along this fault was at least a thousand feet: and I do not know how much more—probably very much more. Along the lines of these east-west faults have ascended dikes and necks of rhyolite, vertically flow-banded, the channels of a second paroxysmal expulsion of lava, which spread out as horizontal flows on the top of the older volcanic surface, whose rocks had become tilted as

[43] BARRELL: Bulletin G. S. A., Vol. XXVIII, pp. 745-904.

well as faulted by the adjustments which followed their ejection and deep accumulation. This later volcanic period also piled up explosion breccias, alternating with flows, to a thickness of probably several thousands of feet.

After the second volcanic outburst and rhyolite intrusion, there was again strong movement along the great fault where now is the Golden Star mine, and in other zones in the intrusive rhyolite; and as soon as this post-intrusion faulting had reopened fissure channels, solutions came from below, and deposited scanty fine quartz, often chalcedonic, auriferous pyrite, and free gold, cementing and replacing weakly the fault breccia.

Let me animadvert a little concerning the type of this vein. I do not plainly recognize it as belonging to the ore-magma series proper; and I am inclined to class it as of the general type of the gold deposits of Aurora (p. 699). It is clearly a near-surface deposit, such as I believe has been deposited by magmatic solutions emanating from deeper ore magmas, and deposited under light pressure. The mineralization has taken place on the under side of the thick fault breccia, showing that this has acted as a relatively difficultly permeable blanket for ascending solutions. I have discussed this type of vein in Chapter XV.

After the ore deposition there was a slight renewal of the movement along this great fault fissure which had thus become locally a fissure vein, a slipping registered by a "gouge" or breccia and *practically horizontal* fault striations; and back of the fault vein, in the rhyolite, this last movement is registered by zones of crushing.

The Golden Star vein, therefore, rests in a fault fissure of earlier origin than the particular magma intrusion with which it is most closely associated in point of contiguity and age—the rhyolite necks and dikes—and, therefore, does certainly in large measure at least fall into my classification of immigrant veins, that slipped into a fissure-home prepared long before by an earlier magmatic episode—a fissure which was on a major structural fault plane. And between

the two volcanic paroxysms—the one that produced the first tilted series of flows and the one that produced the dikes and the more horizontally overlying series of flows—the lapse of time must have been very great, as measured by erosion and fault growth. This fault growth in the interval between the two volcanic paroxysms was a result of sagging or magma collapse after extrusion, and *was chiefly vertical* along the fault plane. I do not know what was the nature of the considerable later movement along the fault plane following the later rhyolite intrusions and preceding the ore deposition. But the marked movement succeeding the ore deposition, and not followed by dike or ore, was horizontal—therefore, a movement resulting from horizontal adjustments on magma consolidation.

CHAPTER XVII

The Influence on Veins of Rock Texture and Rock Structure

This chapter points out that the trend, strength, and openness of fissures is modified by the character of the rocks which they traverse. Veins are weak in soft rocks, like shales. They may acquire a step-like shape in traversing alternate rigid and yielding strata. Lenticular veins are believed to be due to the incrushing of walls in depth, during consolidation of veindikes. Under considerable load, certain rocks under general intrusive stress may be shattered, rather than fissured; and the disseminated type of ore deposit results. Disseminated ores are from aqueous-magma solutions, and are accordingly derived mainly from siliceous-intermediate magmas.

Impervious and soft strata close up traversing fissures, and ascending solutions mushroom out below such dams, and form ore sheets below the contacts.

FISSURING, SPLITTING, OR RIFTING is a relative problem—relative to the rock which undergoes the stress. Some rocks are tough, like limestone or schist; some brittle, like quartzite and granite; some are yielding, like shale; and so on. The same stress will produce fissures in one rock, adjustment by mashing or mechanical flowage in an adjacent one. Where there is a complex of rocks under stress, such as an alternating series of sedimentary formations, or igneous intrusions, or both, then there will be a great variety in the results of stress.

In general, a fairly firm, rigid, and homogeneous rock, breaking clean, strong, long, and deep under stress, is the most favorable for the fissuring which later offers a home for veins. Such conditions are best found in igneous rocks, especially in thick and massive bodies; for these have neither change of nature nor have they bedding planes. This is one—though only a minor one, as the reader will at once appreciate from the foregoing—reason why so many veins are in igneous rock walls.

Where a vein fissure passes, as it frequently does, from one rock into another, the relative strength of the different parts of the fissure shows by comparison the fitness of different rocks, and their effect on fissuring and on traversing solutions.[1] Fissures and even faults in a rigid stratum or rock are often seen to become fainter or even disappear entirely on entering a more plastic rock, as in passing from sandstone into shale. Figure 144 shows the weakening of the Seven-Thirty vein at Georgetown, Colorado, on passing through a porphyry dike, in which the fissure was tighter than was the case in the granite on both sides.

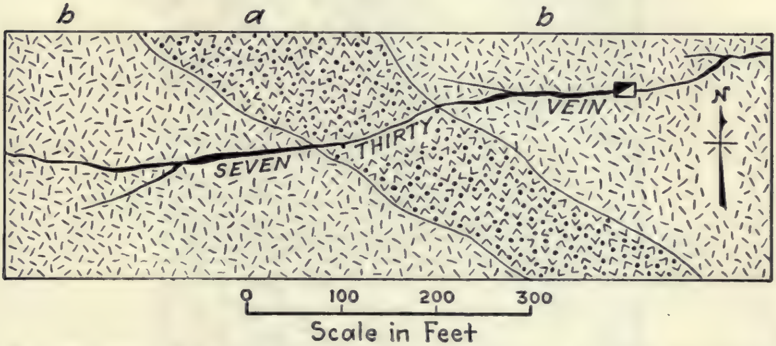


FIG. 144.—Seven-Thirty vein, Georgetown, Colorado. Showing weakening of the vein on passing from granite (*b*) through porphyry (*a*). After Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 48.

Earlier structures in rocks, such as stratification planes, may deflect a fissure, at least for a while, till the impinging stress reasserts itself, and again breaks across. This is illustrated in the accompanying sketch of fissures in the limestone at Mercur (Fig. 145). In a larger way this is

[1] The localization of oreshoots and mineralized portions of veins as the result of the relative brittleness or yielding of different rocks under stress is well formulated by J. A. Reid (*Econ. Geol.,* July, 1918, p. 389) as an explanation for the oreshoots at Cobalt. Here the formations are principally conglomerate, diabase, and greenstones (Keewatin): of these the conglomerate is most brittle, the diabase next, and the Keewatin last, though certain members of the Keewatin are more brittle than others; and the ores show a corresponding preference, characteristically disappearing after crossing the contact from a more brittle to a less brittle rock.

illustrated by fissures crossing a series of sedimentary beds at the Pony Express mine, at Ouray, where the result is a series of "step-veins" or "staircase" veins, if one may so call them (Fig. 146 A and B), these step-veins being a variation of what would be a regularly steeply dipping vein in a homogeneous rock; but in a series of strata separated by

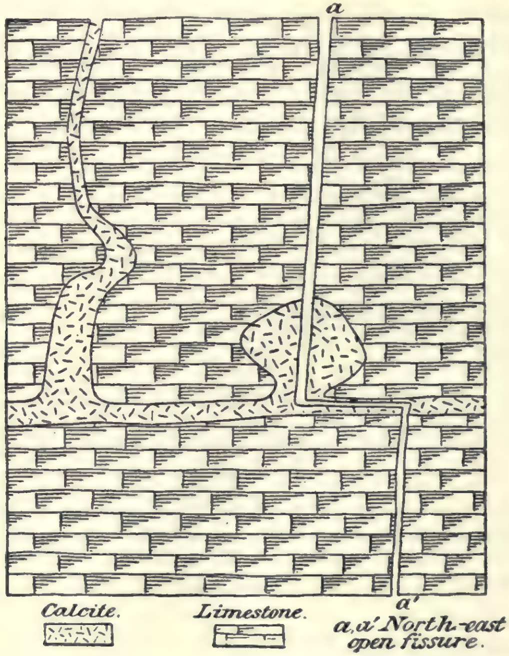


FIG. 145.—Showing "stepping" of vertical open fissure (a) by encounter with horizontal calcite seam. Mercur district, Utah. After J. E. Spurr: Sixteenth Ann. Rep., U. S. Geol. Surv., 1894–95; Fig. 43.

strong bedding planes, such a fissure has partly been deflected by the bedding and to compensate has broken across the beds at right angles to the bedding, as the direction of least resistance (weakest direction). The Pony Express veins in homogeneous rock are, it will be seen, very steeply dipping; and it is easy to understand that if the direction of the natural dip had been flatter, or if the strata had been somewhat inclined toward the direction of fissuring stress,

the stretches of the vein which ran along the bedding planes would be longer, or the stress might even be totally deflected and taken up by a slight differential movement along the bedding plane. Thus so-called "bedded veins" originate, a not uncommon variety—that is, when the ore solutions fill such a "bedded" fissure. Of course, the continuation of stress after ore deposition (which continuation of stress,

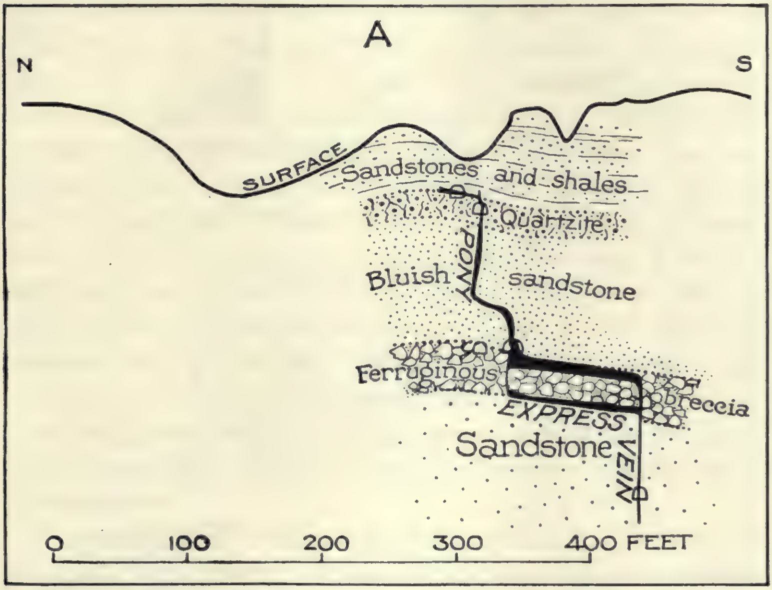


FIG. 146A—Pony Express mine, Ouray, Colorado. Cross-section showing Pony Express vein. Shows, especially, jogging or "stepping" of vein, due to diversion of fissure by stratification planes. By J. E. Spurr, private surveys.

as I have previously shown, typically develops more important differential movement, or more marked faulting, than the pre-mineral fissuring) will also tend to take place along bedding planes in such thin-bedded formations; and thus the important type of bedding-plane faults is formed, by one stratum slipping on another. Note, in the cross-section of the Pony Express vein (146 B), the bedding-plane fault at the top of the figure.

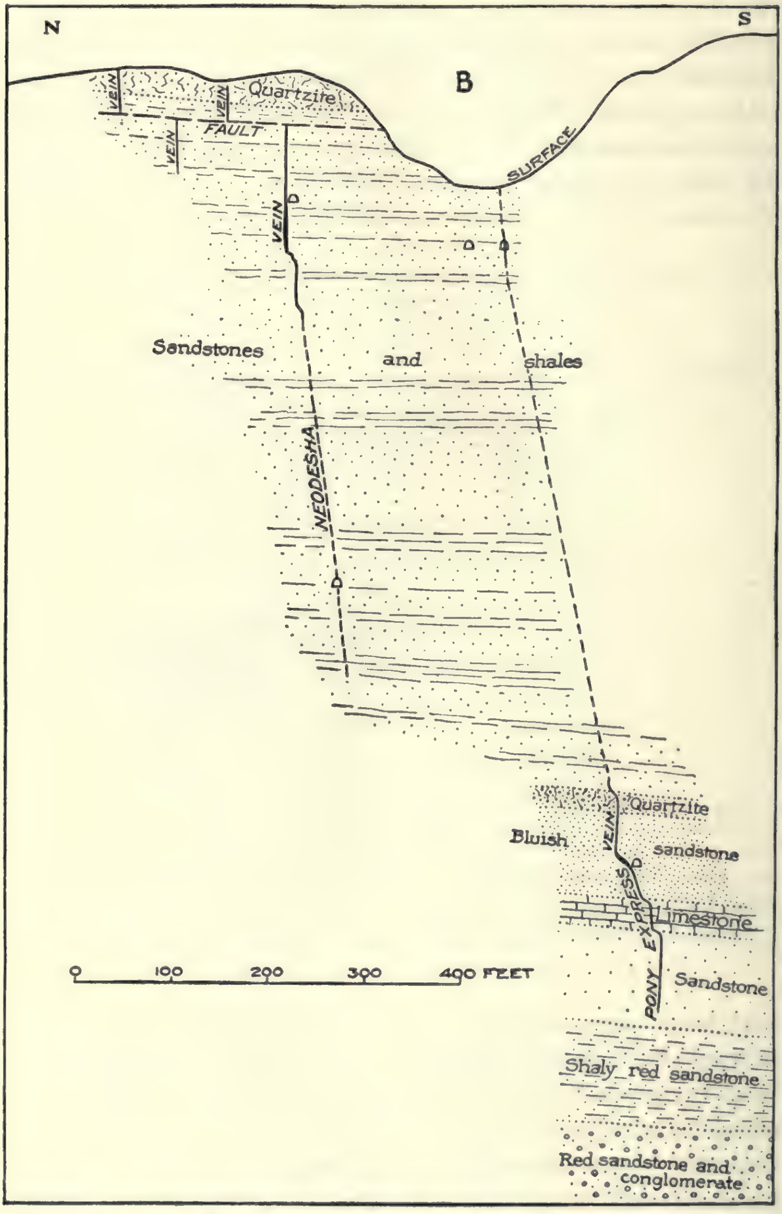


FIG. 146B.—Pony Express mine, Ouray, Colorado. Cross-section showing Pony Express and Neodesha veins. Shows, especially, jogging or "stepping" of veins, due to diversion of fissures by stratification planes. By J. E. Spurr, private surveys.

In general, it is very unfavorable for the strength of a vein for it to pass into shales. The case of the Santa Francisca mine, at Asientos, Durango, Mexico, is a good illustration of this well-known and reliable law.[2] The lode was an extraordinarily wide one, occupying a fault fissure which traversed trachyte and soft shale. The vein was discovered and was mined where the two walls were trachyte; further down shale underlying the trachyte came in on one side of the fault, and consequently the vein had trachyte on one wall and shale on the other. The level where the vein would pass into shale on both walls was easily calculable, and was close beneath; and I accordingly warned the owners of the likelihood of the great impoverishment of the lode on reaching this level. It so happened that an operating official, anxious to gamble for a reputation as an ore prophet, and anxious also that I should lose mine, but without even an elementary idea of geology, made an issue of this warning, and made a corresponding prophecy to the company that the strength of the vein would not be affected if it passed into shale on both walls. Of course, as a gamble, the cards were stacked against him; mining practically stopped when the vein reached the level in question.

The occurrence in schist of veins, which have evidently intruded the schists at considerable depth, offers a special problem. The most common type of such veins are gold-quartz veins, but sulphide veins also occur. Frequently these ores occur as lenses in the schist—usually a string or zone of lenses, sometimes overlapping. At these same depths the veins in solid homogeneous rocks, like granite or other igneous rock, usually have the normal tabular or dike-like form. The lenticular, interrupted vein seems clearly connected with schistose rock. Since this schistose rock has evidently in most cases derived its schistosity from flowing under pressure, it has long been a favorite hypothesis that these lenses of ore are due to deformation—that

[2] See Chapter V, p. 282.

is, that they have been pinched into this shape by pressure on an originally tabular vein. But in the cases which I have examined, this explanation rules itself out, because it is clear that the quartz of the lenses has not yielded to any pressure. The Silver Peak geology[3] offers as good evidence of this as anywhere. In the schist in this district are strings or zones of lenses, not only of gold-bearing quartz, but of alaskite (quartz-feldspar rock), into which the quartz is locally transitional. Neither the alaskite nor the quartz lenses show any effects of strain, whether along their margins or elsewhere: they have not been pinched or squeezed since they consolidated. They do occur along definite zones, showing that the alaskite magma and the quartz magma penetrated from below for a long distance along these zones, and would, therefore, under normal circumstances, have formed continuous intrusive fissure-fillings (dikes, veindikes, or veins, as you please). My first hypothesis was that these magmas had been so thin and penetrant that they had passed through the schist between the lenses (which in part do not connect with one another), and then blown out like boils or bubbles here and there. But in one case which I noted, alaskite aplite, of the same type which forms the lenses, cuts into a solid limestone, which lies on both sides of and above the belt of schist, which was originally a shale formation lying between these massive limestones. The alaskite forms a regular and persistent dike six inches wide in the limestone, and does not show the lenticular structure, while in the schist (derived from the shales) such alaskites are always more or less lenticular.

Therefore, we find it improbable that the magmas seeped through the shale-schist rock, through channels now practically invisible; and we grant that these lenses were once connected. The existence of a former strong series of fissure veins is shown by the frequent plain branching of both alaskite and quartz masses. Now, if (as is the undoubted

[3] *Professional Paper* 55, U. S. Geol. Surv. See Chapters I and II.

case) the alaskite and the quartz show no evidence of crushing or shearing, it follows that the separation of the continuous vein into lenses must have been accomplished after the intrusion of the veindikes of alaskite and of quartz, but before their consolidation. These veindikes, I believe, owed their intrusive power to their gaseous tension (see Chapter III). They exerted a power superior to the incrushing power of the shales; and, penetrating the slightly inclined sedimentary series, they thrust aside the pliable soft rocks, molding the flowage of these rocks to the vein-dike walls—this is shown where strips of shale-schist have been caught between much larger masses of alaskite. As they came to rest, however, they began to lose some of their volatile elements and to decrease in gaseous tension. The result was the incrushing or inflowing of the flexible and soft shale walls, parting the magma into separate trapped lenses; and under these conditions the magma crystallized. In the limestone, however, as in the case where it forms the walls of the alaskite dike above mentioned, the rigidity of the rock prevented local flowage against the magma which had forced open its fissure, and so the walls remained parallel, while the magma crystallized. But in this vein there is a parallel arrangement of the quartz and feldspar which did not take place after, but which took place during, crystallization, which arrangement is probably to be interpreted as a slight flow-structure due to the pressure from the parallel limestone walls (Fig. 7). This flowage took place after the feldspar had crystallized, but before the quartz had crystallized. There is no crushing of either mineral.

Similar rude flow-banding, originating before the final consolidation of the alaskite magma, has been noted in the alaskite lenses in the schist, which are associated with the quartz lenses, whose crystallization history has assuredly been similar, but which cannot be followed so closely as where the lens consists of both quartz and feldspar. In the principal mines, microscopic study of the alaskite

"brings out the fact that the crystallization was rather slow and interrupted, and is represented by more or less distinct generations."[4] One type shows a first generation of coarse quartz and feldspar, while the interstices are filled with fine quartz and feldspar; and the proportion of the two generations varies in different specimens. Another specimen shows a first crystallization of feldspar crystals and a later crystallization of quartz in the interstices between the feldspars; and the quartz sometimes cuts across the feldspars, following cracks. Here then we have evidence of mechanical disturbance of the magma during crystallization, such as we do not usually find in granitic or alaskitic rocks. Moreover, I noted repeatedly that the first-formed feldspars had been considerably altered to muscovite,[5] while the intermediate-formed ones were slightly so muscovitized, and the latest-formed feldspars were quite clear. It seems that muscovite is formed by the action of fluorine on the orthoclase molecule; and I, therefore, inferred the presence of fluorine in the early stages of consolidation, but not in the later stages. This would harmonize with my present assumption of partial loss of gaseous-tension potency by the magma during consolidation, allowing the caving-in of the schist walls and the separation of the magma into lenses.

The same explanation will apply to sulphide lenses like that of the Mandy,[6] which show a sharp contact against the schist wall rocks, indicating a relatively dry viscous magma. The contact indicates intrusion of the sulphides into the schist; and the sulphides have a distinct flow-banding, indicating flowage during crystallization. Although the schist wraps around the sulphide body, yet the flow-banding of the ores is locally and in detail quite unconformable to the schistose structure of the walls. While the schistosity of the rock has been plainly formed

[4] *Professional Paper* 55, U. S. Geol. Surv., p. 40.
[5] *Op. cit.*, p. 43.
[6] See Chapter II, p. 110.

by pressure and largely by mechanical rearrangement, the quite different flow-lines of the ore are plainly due to liquid flowage during the process of crystallization, which in this sulphide ore (as in other sulphide ores) has its distinct succession of crystallization of different minerals, just as there is such a succession in a granite or an alaskite. For such sulphide lenses, therefore, I interpret the sulphide magma (not greatly less in concentration and bulk than in the present ore) as intruded, precisely like a dike of alaskite or pegmatite or quartz—intruded by virtue of its gaseous tension into the schists; and as, in the incipient crystallization, it begins to lose its gaseous-tension strength, I visualize it as yielding here and there to the pressure of the walls and becoming trapped in separate lenses. Such lenses once being trapped, of course there is an end of the incrushing power of the walls, and crystallization goes on; but if, as was probably the case with the Mandy sulphide body, the crystallization was partly completed at the time of the separation of the magma-filled fissure into lenses, then in the crystallizing sulphide magma there would be developed the fine, streaky flow-structure so strikingly shown in this ore. The flow-structure of such sulphide lenses has been ascribed to cold flowage under pressure, together with the schist walls; but this explanation cannot apply to the Mandy, where the schistose rocks of the walls have been intruded crosswise by tongues of the liquid sulphide magma.

The lenses in schist, which seem to have the origin above given, are chiefly alaskite, pegmatite, quartz, gold quartz, and massive sulphides of copper and of zinc. Pegmatite lenses are very common in this form, and their unbroken crystalline fabric shows that they have crystallized in place, as lenses, and have not been crushed since consolidation. I have not, however, commonly found igneous rocks more basic than the alaskites occurring in this habit. If this lenticular habit was due simply to cold crushing, one kind of igneous rock should occur in this habit as often as

another. But granites, diorites, and diabases usually retain a connected dike-like form, even when we find them in schists. This is well shown by the diorite dikes of Silver Peak, which I interpret as having been intrusive immediately after the quartz magma. This would indicate a greater resistant strength against the pressure of schist walls in the case of the ordinary igneous rocks than in the case of the more extreme magmas, like the magmas of alaskite, pegmatite, quartz, or sulphides. Indeed, a greater liquidity of pegmatite magma, for example, than diorite magma is shown by the fact that the former, when it lies in schist, does penetrate and intrude between the laminæ quite intricately. At Silver Peak, for example, I have recorded[7]: "These masses of alaskite and quartz have been intruded into the bedded shaly limestone and are generally intercalated in the strata in large and small sheets, although they are in places cross-cutting. The intruded sheets vary in thickness from many feet to the tenuity of a sheet of paper, and are in places interlaminated with thin plates of schist, like the leaves of a book." The more basic igneous rocks do not occur in this way; although granite approaches or practically reaches this habit. Diorite and diabase, however, I believe, do not so occur[8]; and from this we may reason that dikes of the more volatile magmas —that is to say, the more siliceous magmas, like granite, alaskite, pegmatite, and quartz, together with sulphide magmas—have, during congelation, less resistant power against incrushing schist walls. We cannot, however, doubt the enormous intrusive potency of granite; and the frequent reduction to the lenticular form of these extreme siliceous rock magmas and of the ore magmas, in schist walls, evidently depends, as above outlined, on the fact that so much of the gaseous-tension strength is eliminated during crystal-

[7] *Professional Paper* 55, U. S. Geol. Surv., p. 40.

[8] Where a complex mass is actually crushed, as sometimes happens, any rock, of course, may be reduced to shreds and fragments, often lenticular in shape.

lization, while in the case of the more basic rock magma this is true to a much less degree, and those more basic magmas which do succeed in intruding a foreign rock undergo comparatively a less loss of resistant or tension strength up to the time of consolidation.

In some cases rocks have shattered under strain, without definite persistent fissures having been developed. The main copper deposit at Ray, Arizona,[9] is an instance of this. For a belt whose horizontal length is over 12,000 feet, and whose horizontal width is from 1,000 to 3,000 feet, the pre-Cambrian schists in this camp have been thoroughly shattered, although without the development of important and definite fissure systems; and subsequently the whole rock has been permeated with magmatic ore solutions and, as a consequence, with cupriferous pyrite, forming the original or primary ore of this great copper deposit.

The pre-Cambrian schist in which this ore lies is overlain by Cambrian quartzites and by Paleozoic limestones. Probably near the close of the Cretaceous period, diabase ascended in dikes through the schist, spread out as thick sheets at the base of the quartzite, and sent dikes into the overlying strata. Later, a great mass (batholith) of granite porphyry welled up from below, through the schists, sending small dikes into the overlying strata. The Ray district lies on the borders of this batholith, in the overlying schist, which is cut by dikes and protuberances from the main mass not far below. The ore-magma solutions followed, in point of time, the granite porphyry intrusion and the beginning of faulting which accompanied the intrusion or ensued. The sheets of rock which immediately overlie the schist—diabase and quartzite—appear to have exercised a blanketing influence on the solutions, which spread out beneath these capping rocks and permeated the schists and the granite porphyry, forming the "disseminated" deposits. A smaller part of the solutions escaped through fissures (generally along faults) into the overlying strata, and there

[9] See Chapter IV, p. 224.

formed fissure veins or lode deposits, sometimes with impregnation of the wall rocks with cupriferous pyrite.

This solution was, therefore, plainly an aqueous or "pegmatitic" one, which is theoretically consistent with its derivation from a siliceous (granite) magma. Indeed, all the disseminated copper deposits were probably, from their very nature, formed from the aqueous or pegmatitic type of ore-magma solution; and accordingly we find them invariably derived from intermediate siliceous magmas. They do not occur in connection with basic magmas, although basic magmas may be cupriferous (Chapter XII).

In a more general way, also, this limitation probably applies to that class of deposits which are closely allied to the disseminated deposits—the replacement deposits; and this is true whether they are replacement deposits accompanied by the silicification of limestone or other rocks or those accompanied or preceded by the lime silication (at a higher temperature) of limestone or other rocks. Doubtless the relatively dry ore magmas characteristic of derivation from basic magmas do replace limestone in some degree, as has been reported from Kennecott,[10] in Alaska; but it is plainly a weak and restricted process as compared with that attendant on the intermediate siliceous igneous invasions.

The influence of relatively impermeable strata, such as shales or decomposed sheets of igneous rock, on ore deposition is of the utmost importance. Given a series of bedded rocks, traversed by a fissure system, the fissures will almost or quite close when they enter this type of soft or yielding rock, as I have stated in discussing fissure veins; but above such a soft bed they very often continue in a harder stratum, although sometimes the differential movement which caused them may be taken up wholly by such a soft stratum, if the movement has been slight and the stratum ample. Now, when an aqueous ore-magma solution rises

[10] A. M. Bateman and D. H. McLaughlin: *Econ. Geol.*, Vol. XV, No. 1, p. 20.

from the depths along these fissures in the rigid rocks, and encounters a bed where the yielding softness has resisted fissuring, the soft layer acts as a dam or blanket, and the solutions are partly or wholly dammed, and under the pressure from below they mushroom out, spreading out below this impervious contact. This is a principle of ore deposition as important as the existence of fissures. It is well shown in Fig. 68. The traversing fissure is a slight fault, which I called the Maid fault. Passing upward from the granite, this traverses obliquely the Paleozoic strata and intrusive sheets of porphyry. The thin bed of "Parting quartzite," a more or less shaly rock, has dammed back the solutions rising along this fissure, and an orebody has formed below it by replacement of the Silurian limestone ("White lime"). Further up, the ore-magma solutions were dammed back by an intrusive sheet of monzonite porphyry ("Gray porphyry"), and in the same way an orebody was formed beneath this rock, by replacement of the Carboniferous limestone ("Blue lime"). Still higher up the fissure cuts a thick overlying intrusive sheet of alaskite porphyry ("White porphyry"), and again beneath this an orebody was formed by replacement of the "Blue limestone." Fig. 68 is on a plane which shows the history in the plainest way; another cross-section, taken some distance away, shows precisely the same oreshoots, but extending further along under the impervious contacts as ore-sheets. Such an extended ore-sheet is seen under the alaskite porphyry on the left side of the section shown.

The section incidentally shows that ore solutions, certainly those of the more aqueous type, can pass along a fissure and leave little trace—at least, form no vein or ore deposit till conditions cause the precipitation of the solid constituents.

The subject of the effect upon veins of physical variations in wall rocks is one on which a volume might be written; but I will not undertake here to go further into detail.

CHAPTER XVIII

The Succession of the Earthy-Mineral Veins

This chapter states that there is a sequence among the barren earthy-gangue veins, which characteristically follow the sulphide ore veins and are the last of the magmatic veins. These barren-gangue veins do not bear evidence of having been deposited from water, but bear evidence of having been intruded as jellies or gels. Their sequence shows that in general the mixed carbonates (of lime, magnesium, manganese, and iron) form an earlier stage, calcite a later one. Quartz has no fixed position, nor fluorite. Iron as carbonate registers a lower temperature than iron sulphide in the ore stage, which in turn is lower than iron oxide and silicate in the rock stage. Arsenic and antimony constitute barometer-thermometer minerals: their plain sulphides are characteristic of the post-ore earthy gangues and the solutions residual from these. Hot-spring waters are those residual from any stage of magma consolidation, whether rock magma, ore magma, or earthy-gangue magma.

Differentiation is geologically not a very slow process, completing itself as part of a cycle of intrusion, refrigeration, rock adjustment, and rock and ore differentiation. The bottom of the zone of differentiation does not migrate downward with the downward-migrating zone of refrigeration above; it remains fixed by opposing pressures. When these are finally unbalanced, especially by erosion, a new cycle of intrusion, differentiation, and ore deposition arrives.

THE EARTHY MINERALS, such as quartz and calcite, not only form gangue contemporaneous with the sulphide stages, but, in typical magmatic metalliferous sequences, persist beyond the metal-depositing period, and form barren fissure veins, which differ as to their composition, and have in different districts a distinct sequence. At Velardeña, for example, I have described[1] the post-metallic sequence (coming after the rich silver-sulphide stage, which had chiefly a quartz gangue) in the important Terneras vein, as, 1, Mixed carbonates (of iron, magnesium, manganese, and lime) and quartz; 2, coarse

[1] *Econ. Geol.*, Vol. III, No. 8, p. 714.

calcite, often brown from inclusions of iron oxide. The Caldas vein shows a first stage of arsenopyrite, with a later filling of mixed carbonates, containing intercrystallized realgar, probably derived from the earlier arsenopyrite. This mixed carbonate vein has crystallized as a fissure-filling, for it shows next the walls gray ankerite (magnesium-lime-iron carbonate) with comb structure, and white dolomite (magnesium-lime carbonate) in the center.

This derivation of realgar from earlier arsenopyrite, by a subsequent stage of certainly ascending hot solutions, coincides with the observations of Ferguson at Manhattan, in Nevada, as mentioned in Chapter XI. In discussing the peculiar problems of realgar versus arsenopyrite in this chapter, I came to the conclusion that the latter was formed only under considerable pressure, by typical ore magmas, while realgar was formed at a lower pressure, and was deposited by magmatic hot waters and vapors residual from crystallization of the ore magmas. Differences in temperature, I pointed out, could not satisfactorily account for the evident sharp demarcation and distinction of the conditions under which these arsenic sulphides were formed, for realgar was formed in volcanic fumaroles, while arsenopyrite has not been recorded under such conditions. If, as I later reasoned, and as I believe, the ore magmas are in a state of gaseous tension, and are at a temperature and pressure above the critical points where certain elements of the magma such as water pass from the liquid into the gaseous-tension stage, then it is probably the repressed gaseous-tension condition of the ore magma which will make possible the combination of arsenic and iron sulphides to form arsenopyrite; whereas the pressure-temperature conditions below that critical for the gaseous-tension ore-magma condition do not favor the formation of arsenopyrite, but of the simple arsenic sulphide, realgar. Realgar and arsenopyrite, then, seem to be mineral criteria, geologic barometer-thermometers, registering respectively liquid (or gaseous) residual solutions and the contrasted true ore

magmas. The fact that realgar is not found in the metallic zones normally occurring (in the regular mineral sequence) above the arsenopyrite zone—for example, in the galena-blende or rich silver (tetrahedrite, etc.) zones which contain complex arsenic-bearing minerals, like polybasite, tennantite, and proustite—seems to confirm my conclusions that in all these zones the ore magma remains intact. Accordingly, the abundant occurrence of sulpharsenides in Tertiary bonanza veins, which have formed at shallow depths, and in which realgar is lacking, coincides with my earlier reasoning that these were formed by true ore magmas, like those in greater depth, and not by hot springs. I showed in these cases that the requisite temperature, similar to that attending the formation of the deeper veins, was easy to account for.

Therefore, it appears likely, by the realgar criterion (as applied to the Caldas vein above), that the barren-gangue veins, which in most mining districts succeed the sulphide-bearing veins, are residual from the metalliferous ore magmas, while all the various stages or zones of sulphide veins are formed by ore-magma solutions, probably above the temperature critical for water (365° C.). But there are considerations which still stand in the way of our accepting the conclusion (to which we are always fain to jump, from our knowledge of hot springs and our unfamiliarity with magmas), that these liquid aqueous solutions which we infer have formed the barren-gangue veins were hot mineral waters, such as emerge as hot springs. Crustification or fine regular banding is wanting in many of these veins, such as the mixed-carbonate veins at Velardeña concerning which I am writing. There is a sequence, as noted above, for the Caldas vein, of ankerite on the walls and dolomite in the center, which shows that crystallization was not simultaneous; still the roughness of this sequence indicates rapid filling of the fissure, and does not indicate dilute solutions any more than does, in the case of the galena-

blende sulphide magma, the first deposition on the walls of quartz, and the later infilling with sulphides (see p. 677).

Another very significant thing is the presence of unsupported angular inclusions in these gangue veins, just as we have noted them in the ore veins. Fig. 147, showing a vertical section of the vertical Terneras vein, which I drew very carefully, illustrates this.

This section shows the following vein history: **1**, The intrusion of a vein, seven inches wide, of massive cupriferous, argentiferous, and auriferous pyrite (values per metric ton: gold, 60 grams; silver, 3,690 grams; lead, 7.9 per cent; zinc, 3.8 per cent; copper, 3 per cent); **2**, the fissuring along one wall of the **1** vein, and the filling into the fissure, of a vein eight inches wide, of very coarse galena and blende (gold, 1 gram; silver, 3,023 grams; lead, 38.9 per cent; zinc, 27.1 per cent; copper, 1 per cent); **3**, the splitting of the **2** vein down the middle, and the infilling of the fissure by a vein one foot wide, of fine earthy carbonates and quartz, with finely disseminated sulphides.

While **1** and **2** veins show no signs of banding, but register simultaneous consolidation, this **3** vein is banded, especially near the walls, where there is an especially clear banding produced by narrow streaks of sulphide (a quarter to an eighth of an inch thick) alternating with streaks of the gangue one and a half to two inches thick. The rest of the vein shows traces of banding, but more of granular crystallization, the sparse sulphides being disseminated in the gangue. This (**3**) is essentially a barren-gangue vein (gold, a trace; silver, 74 grams; lead, none; zinc, 0.6 per cent; copper, a trace). The succession of banding near the walls shows no trace of change of composition of the precipitating solutions to account for the successive deposits, but a rhythmic repetition or alternation of precipitation from a solution of sparse metallic sulphides and predominant earthy minerals, and later a nearly uniform crystallization of the same mixed solution, in the same proportions. This suggests that during the whole period of consolida-

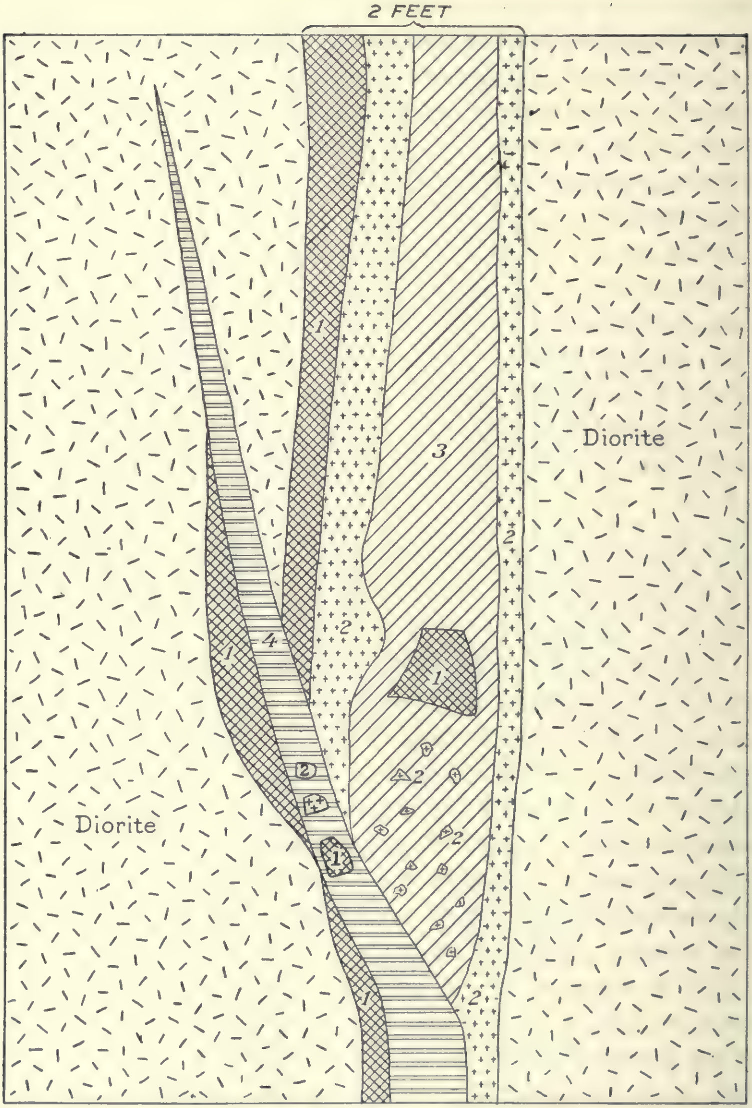


FIG. 147.—Velardeña, Durango, Mexico. A vertical cross-section of the Terneras vein, showing successive stages. 1, Massive pyrite and quartz; 2, coarse galena and blende; 3, earthy carbonates and quartz, with disseminated sulphides—contains isolated inclusions of 1 and 2; 4, barren coarse calcite. Shows intrusive nature of each stage, and ability of magma such as that of 3 to support angular inclusions of heavy sulphides. By J. E. Spurr.

tion of the **3** vein the fissure was full of the same solution, which held open the fissure by its pressure; and that the banding was due to the crystallization of this solution, proceeding from the walls outward into the unconsolidated solution. This would argue a highly saturated solution, with the water near the minimum required for solution under the local temperature and pressure, although we may provisionally assume, as above stated, that the water was in liquid form, and below 365° C. The presence of sparse sulphides shows that the solution, when it passed out, as a residual liquor, from the ore-magma solutions (represented by veins **1** and **2**), took with it in solution some metallic sulphides, but the comparison of the quantities recorded in the assays is eloquent of the difference, in metallic content and control, between the ore magmas and their residual solutions, for in this case the latter contained only 2 per cent, for example, of the silver in both the earlier ore magmas (the silver being taken because it alone occurs in about the same proportion in veins **1** and **2**, and, therefore, appears to be persistent). Of the zinc, again, in vein **2**, immediately preceding, vein **3** has salvaged only a little over 2 per cent, a striking check on the silver extraction.

Vein **3** also incloses, as shown in the drawing, angular, isolated, unsupported fragments, of various sizes, of veins **1** and **2**. Moreover, an inspection of the relation of the principal included block of **1** shows that it has not been derived from that section of the solid vein **1** included in the drawing; that it has, indeed, been floated to its present position from a point outside the section. I say "floated," for it occurs isolated in the vein, and, therefore, must have been suspended in the fluid solution. Yet evidently the block is of a higher specific gravity than the surrounding vein; and how much more is this evident for the fragments of the galena-blende vein **2** in this calcite-quartz vein! Here we have a problem to be confronted squarely, for we shall meet it in many places. The confining of the included fragments to the lower part of the section may possibly mean

(for the whole circumstances are not displayed) that the included fragments tended to settle in the inclosing fluid. But this tendency was very slight, and not enough to cause them to descend till they found support. The separation of the block of **1** vein from the **1** vein in place, by the later **2** vein, renders utterly untenable any attempt to apply the theory (for which indeed I find little application anywhere) that the block was split off from the vein by the force of crystallization of the **3** vein. It is inevitable that these heavier blocks were supported free in the lighter solution. No escaping the conclusion that the solution was viscous—that it was, indeed, in the form of a gel or jelly—just such a jelly as has been shown may consolidate in rhythmic bands, from the walls out, as this vein has done (p. 521). If this conclusion is correct, then we may deduce the further general rule that the first liquid residues from the ore magma are, often at least, earthy gels or jellies of silica, of the mixed earthy carbonates, etc., which may act as intrusives, forcing open and filling fissures. For we cannot believe that any of these fissures were yawning and empty before the infilling. Their persistency indicates the existence of fissures so continuous that the rock pressure on the walls would have forced them shut, had they no internal pressure as support. Fissuring and infilling were simultaneous operations: the rocks separated through the pressure of the incoming gelatinous earthy residual material. We then come to acknowledge the barren-gangue **3** vein as probably the last stage of the ore-magma sequence, although we surmise that this residual magma was below the critical temperature of water, as the metalliferous ore magmas proper were above that point.

The **3** stage is not the last vein stage shown in the section. A still later fissure-filling is of barren coarse calcite, with comb-structure perpendicularly to the walls (**4**). Even this includes unsupported angular fragments of the **1**, **2**, and **3** veins! Have these been possibly split off from the older veins by the crystallizing minerals? Study the block

of the **1** vein, for example. This explanation does not seem applicable. The width of the **4** vein remains uniform where this block is included. Must we then consider that this crustified, coarse calcite vein was inserted in the fissure as a gel or jelly, and so could carry along and support heavier fragments? I fear we must. I do not see how we can get away from it, much as my mental habits would like to have me do so. For another carbonate vein—a manganese-iron carbonate vein at Georgetown, inclosing angular fragments of earlier blende—the Griffith vein[2] (see p. 140), I was driven to this conclusion early in this discussion: but I have stubbornly refused to acknowledge till now that the crustified, coarse calcite veins which form the final stages of ore deposition in so many districts may have thus been intruded in gelatinous form. However, there are compensations for every pain. This conclusion to which I am unwillingly driven here by logic explains the unsupported angular inclusions of rhyolite in the altogether similar crustified calcite vein at Tonopah, for which I have never been able to find any explanation whatever[3] (Fig. 148). (See p. 710.) It is really disappointing to be continually baffled in my upward search for the "mineralizing waters" which formed veins—proceeding up from the innermost rock magma, where, of course, they were not expected to reside. I apparently have not reached them in my search, while I have climbed the ladder of the ore zones, and up into the barren-gangue veins beyond. However, it is true that it is otherwise very difficult to explain the wide fissure veins filled with calcite, so characteristic of many districts, except by allowing an intrusive potency to the calcite solution.

At Matehuala the last magmatic stage was calcite, in wide veins, preceded by barren, crystalline quartz veins. In one locality, also, celestite was observed as a separate wide

[2] J. E. Spurr: *Professional Paper* 63, U. S. Geol. Surv., Plate XV A, Fig. 107.

[3] J. E. Spurr: *Professional Paper* 42, U. S. Geol. Surv., Fig. 15.

fissure vein, earlier than the calcite. One sequence at Matehuala is shown in the accompanying drawing (Fig. 149), which proves the following history: Alteration of monzonite to barren white and very pale-green pyroxene rock; fissuring, and infilling of the fissure with dark-green garnet and hornblende, without sulphides (1); 2, fissuring

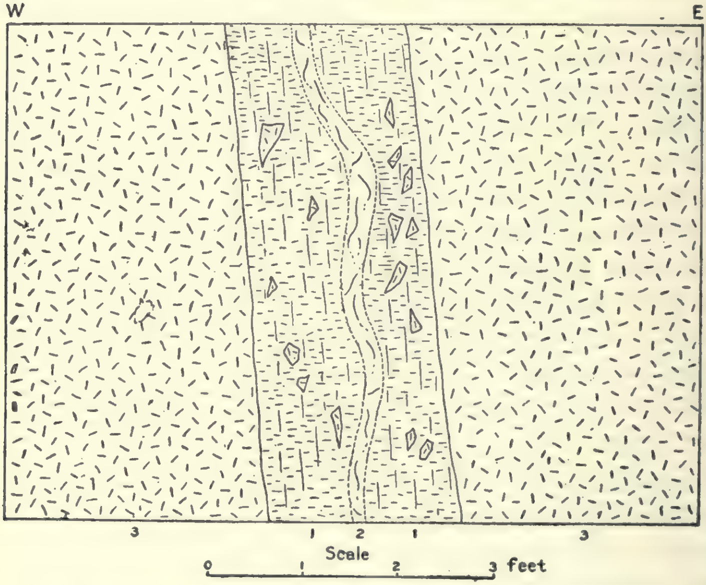


Fig. 148.—Barren calcite vein, banded parallel to walls. Tonopah, Nevada. Calcite vein (1) has been split open and the fissure filled with quartz (2). Note angular inclusions of rhyolite (3) in the calcite vein. What held them there while the calcite crystallized? After J. E. Spurr: Professional Paper 42, U. S. Geol. Surv.; Fig. 15.

of the vein **1** along the center, and filling of the fissure with chalcopyrite, galena, arsenopyrite, pyrite, calcite, and fluorite, all intercrystallized; 3, the formation of a fissure transverse to the 1+2 fissure, and the infilling of it with barren quartz, with a very little cupriferous pyrite (this is the first of the barren gangues, and the scant sulphides corresponds to the scant sulphides in the **3** vein of the Terneras compound vein, which I have just described,

showing again how little of the metals the residual fluid extracted from the ore magmas proper); 4, splitting of No. 3 vein down the center, and infilling of the fissure by barren calcite. And that is the end of the true magmatic sequence, here and elsewhere, just as the rock magma is the beginning.

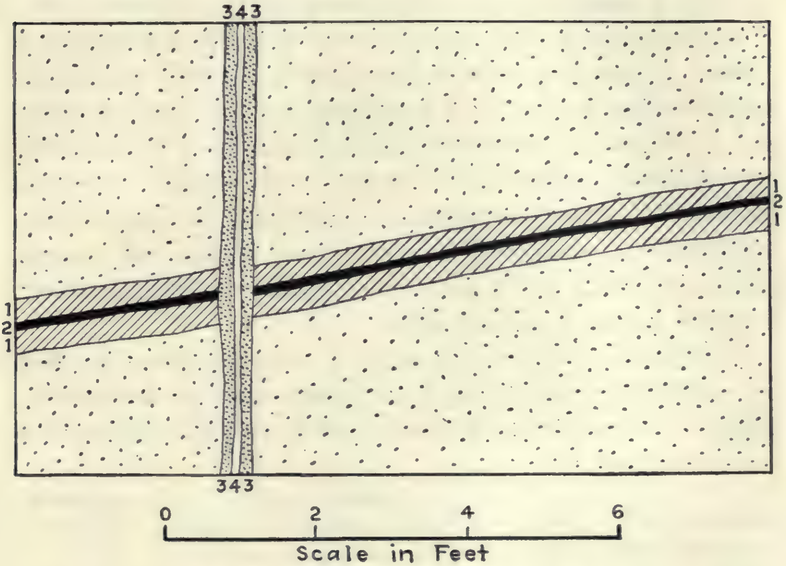


FIG. 149.—Dolores mine, Matehuala, San Luis Potosi, Mexico. Showing sequence of deposition in a typical "contact-metamorphic" ore deposit. Veins in hard white metamorphosed monzonite, altered mainly to secondary silicates. Sketch of wall of drift in San Miguel tunnel. Horizontal (earlier) vein: 1, Dark-green lime-iron silicates; 2, chalcopyrite, galena, arsenopyrite, pyrite, calcite, and fluorite; ore period. Vertical (later) vein: 3, Quartz and sparse pyrite; 4, barren calcite.

At the Silver Lake mine, in Silverton, Colorado, I have recorded, as occurring immediately after the sulphide ores (galena and blende, and cupriferous pyrite), the following barren gangues, filling fissures: 1, Mixed carbonate (of manganese, magnesium, iron, and lime), carrying only occasional sulphides; 2, dense quartz, with a little pyrite; 3, barren calcite. At the Aspen mine, in Silverton, after the same sulphide ore stages of fissure-filling, I noted the following

barren vein stages, each filling its own newly created fissure: 1, Dense, finely crystalline quartz, with only a little sulphides; 2, fluorite and calcite, contemporaneous. In the Inde district, Durango, Mexico, I have worked out the following general vein sequence: 1, Slightly cupriferous and auriferous pyrite, with lime-silicate gangue; 2, auriferous arsenopyrite, with some galena, blende, etc.; 3, cupriferous pyrite, blende, and slightly argentiferous galena; 4, quartz veins with some pyrite, blende, and highly argentiferous galena. This constitutes the ore sequence, and is the same general sequence (cupriferous pyrite, with lime-silicate gangue; auriferous arsenopyrite; blende-galena; argentiferous galena) as shown at Matehuala. Immediately after the ore sequence comes the barren earthy-mineral vein sequence: 1, Mixed carbonate veins; 2, barite veins; 3, calcite veins.

Tabulating, for such correlation and deduction as may be permissible, the above few typical cases of the barren-gangue vein sequence which followed immediately on the ore-vein stages:

	EARLIER STAGES	LAST STAGE
Velardeña (Terneras vein)	"Mixed carbonates" and quartz	Calcite
Velardeña (Caldas vein)	"Mixed carbonates" and barite	
Matehuala	Quartz, celestite	Calcite
Silverton (Silver Lake veins)	"Mixed carbonates" and quartz	Calcite
Silverton (Aspen veins)	Quartz	Fluorite, calcite
Inde	"Mixed carbonates" and barite	Calcite

An inspection of this record indicates that the essential critical and distinguishing law of the earthy-vein sequence is that of the carbonates, by which those of manganese, iron, and magnesium (as well as rare strontium, as at Matehuala) belong exclusively to the earlier stage, while the large veins of plain calcite represent the later and the last magma stage. The other earthy minerals are not so significant as the carbonates. Quartz, it will be noted, is sometimes earlier than the mixed carbonates, sometimes later than them, and sometimes contemporaneous with them. Barite,

scantily observed, seems also to be either contemporaneous or later than the mixed carbonates.

As a check on my conclusions as to the relative sequence of mixed earthy carbonates and calcite, as derived from

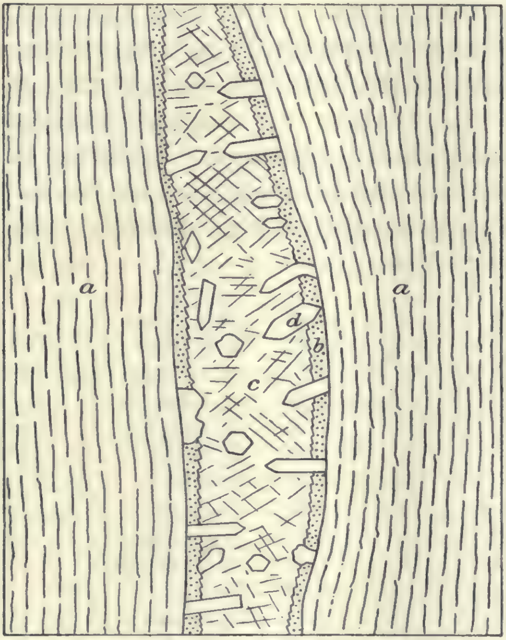


FIG. 150.—Georgetown, Colorado. Veinlet near Mendota vein; natural size. Shows relative periods of deposition of siderite, calcite, and quartz, in a filled fissure. The fissure is in a gneiss wall rock (a). The first deposit on the walls was siderite (b), and then came calcite (c), while quartz (d) grew during the whole period of fissure-filling. Compare Fig. 113, and Fig. 151 from the Colorado Central mine. This Mendota veinlet, in my opinion, represents the "casing" period alone; and, the veinlet being small, it was entirely filled with this deposition. In a larger fissure from the same solutions, I am satisfied that solid sulphides would have occupied the center of the vein.

my study of the sequence of strong fissure veins in various districts, I present the accompanying drawing which I made of a veinlet in the Mendota mine, in Georgetown, Colorado (Fig. 150).[4]

[4] *Professional Paper* 63, U. S. Geol. Surv., p. 240; Fig. 86.

Considering, then, the predominant and significant earthy carbonate veins, we are struck by the fact that the metallic bases (lime, magnesium, iron, manganese, barium) which they represent are among the commonest ones of basic magmas. They are also among the commonest constituents of the earth's crust, and, therefore, are more representative or suggestive of uniform extractive processes than are the metallic minerals characteristic of the veins formed by the sulphide ore magmas, which precede the carbonate ore-magmatic residues. Following is the list of elements in the order of abundance, in the earth's crust,[5] with those characteristic of the magmatic earthy carbonate veins in heavy type.

1. Oxygen	46.43	23. Lithium	0.003
2. **Silicon**	46.43	24. Copper	0.002
3. Aluminum	8.14	25. Cerium, etc.	0.001
4. **Iron**	5.12	26. Glucinum	0.00XX
5. **Calcium**	3.63	27. Cobalt	0.00XX
6. Sodium	2.85	28. Boron	0.000X
7. Potassium	2.60	29. Zinc	0.000X
8. **Magnesium**	2.09	30. Lead	0.000XX
9. Titanium	0.629	31. Arsenic	0.000XX
10. Phosphorus	0.130	32. Cadmium	0.0000XX
11. Hydrogen	0.127	33. Tin	0.0000XX
12. **Manganese**	0.096	34. Mercury	0.0000XX
13. Fluorine	0.077	35. Antimony	0.0000XX
14. Chlorine	0.055	36. Molybdenum	0.0000XX
15. Sulphur	0.052	37. Silver	0.00000XX
16. **Barium**	0.048	38. Tungsten	0.00000XX
17. Chromium	0.037	39. Bismuth	0.00000XX
18. Zirconium	0.028	40. Selenium	0.000000XX
19. Carbon	0.027	41. Gold	0.000000XX
20. Vanadium	0.021	42. Bromine	0.000000XX
21. Nickel	0.019	43. Tellurium	0.0000000XX
22. **Strontium**	0.018	44. Platinum	0.0000000XX
			100.000

Since these elements were contained in the ore-magma solution, from which they have been eliminated by the

[5] H. S. Washington: "The Chemistry of the Earth's Crust." *Journal of the Franklin Institute,* Dec., 1920, p. 777.

consolidation of the metallic or ore-sulphide component, we see how representative of both common and rare elements the typical complete original ore magma is; but a consideration of the relative bulk of ore-magma veins and subsequent barren earthy-gangue veins shows that the proportion differs from that in rock magmas, by an immense concentration of the metals (which are among the rarer earth-elements), just as every other line of inquiry leads us to this same conclusion.

But it is not alone the principle of relative abundance which has determined the grouping of iron, calcium, magnesium, manganese, barium, and strontium, as the characteristic elements of the ore-magma residue and, therefore, the post-ore earthy veins. Chemical affinity has clearly determined the association, in larger measure. Most of the elements which occur in the table interspersed between those just mentioned are those which enter into the composition of acids rather than that of bases: such, for example, are oxygen, silicon, phosphorus, hydrogen, fluorine, chlorine, and sulphur. Carbon, of course, is, as a component of an acid, pre-eminently represented in these carbonate veins. But aluminum, potassium, and sodium, titanium, zirconium, vanadium, and nickel are bases, whose absence in this stage of magma differentiation—the earthy carbonate vein stage—is plainly due to chemical affinity laws. The bases of the carbonates that are represented in the stage in question are largely those of group 2 of the periodic classification of the elements which are classed by Washington as petrogenic elements (making up rocks), while the rest of group 2 are classed as metallogenic elements (making up ores); and the aforesaid bases, moreever, include iron and manganese, also classed by Washington as petrogenic elements.[6] I copy the following table (p. 808) from Dr. Washington's article.

Of these bases, iron, though abundant in this earthy carbonate stage as iron carbonate, plays no favorites in this

[6] *Op. cit.*, p. 780.

Periodic Classification of the Elements.

	Group 0	Group 1		Group 2		Group 3		Group 4		Group 5		Group 6		Group 7		Group 8
1			H 1													
2	He 4	Li 7		Gl 9.1		B 11		C 12		N 14		O 16		F 19		
3	Ne 20		Na 23		Mg 24.4		Al 27.1		Si 28.3		P 31		S 32		Cl 35.5	
4	A 39.9	K 39.1		Ca 40.1		Sc 44.1		Ti 48.1		V 51		Cr 52.1		Mn 55		Fe 55.9 Co 59 Ni 58.7
5	..		Cu 63.6		Zn 65.4		Ga 70		Ge 72.5		As 75		Se 79.2		Br. 79.9	
6	Kr 82.9	Rb 85.5		Sr 87.6		Yt 88.7		Zr 90.6		Cb 93.5		Mo 96		..		Ru 101.7 Rh 103 Pd 106.5
7	..		Ag 107.9		Cd 112.4		In 115		Sn 118.7		Sb 120.2		Te 127.5		I 126.9	
8	Xe 130.2	Cs 132.9		Ba 137.4		La 138.9		Ce 140.3		..		..		..		
9	..		..		..		..		..		..		..		..	
10	..	..		..		Rare Earth Metals. ..		..		Ta 181		W 184		..		Os 191 Ir 193.1 Pt 195.2
11	..		Au 197.2		Hg 200.6		Tl 204		Pb 207.2		Bi 208		..		..	
12	..	..		Ra 226		..		Th 232.5		..		U 238.2		..		

regard: it is equally characteristic of the preceding ore or sulphide stage, as iron sulphide, and of the still earlier oxide-silicate stage as iron oxide and silicate. As a constant base, therefore, it serves to record the three residual or ore-magma stages: the oxide-silicate stage, transitional from and immediately succeeding the rock-formation stage; the sulphide stage, the ore stage or metallogenic stage par excellence, which is transitional from and immediately succeeds the oxide-silicate stage; and the carbonate stage, as we have seen, transitional from and immediately succeeding the sulphide stage. We know that this succession of three stages, from igneous rocks to barren earthy-gangue veins, is accompanied by a falling temperature.

Let us see if the known surface volcanic phenomena can throw any sidelight on these mysteries, which always transpire in the hidden depths of the earth, where we may never observe them, nor discover their results till millions of years shall have passed. The observations on volcanic fumaroles which have been made help us this much, that they show (at least as frequently reported) in general four stages with declining temperature: the first (over 500° C.) containing no sulphur or carbon dioxide, but compounds of chlorine, fluorine, boron, and phosphorus; the second, characterized by sulphur dioxide; the third, by hydrogen sulphide; and the fourth by carbon dioxide (and nitrogen). This is my grouping of the observation data made by French and Austrian observers, and recorded in various summaries.[7] Detailed and adequate temperature data I have been unable to find, and, indeed, the application of it to our vein problem would be doubtful; for the pressure factor, as we have seen, is also of great importance in considering the origin of veins; but the fumarole sequence does correspond with the sulphide-carbonate sequence noted above for magmatic veins, and it does coincide with the finding that sulphide veins are not deposited at the highest

[7] Beyschlag, Vogt and Krusch, Translated by S. J. Truscott, Vol. I, p. 133.

temperature, but at an intermediate temperature, below that of the igneous rock, and above that of the carbonate veins.

This grouping of successive magmatic vein stages according to the acid or gaseous component which combines with

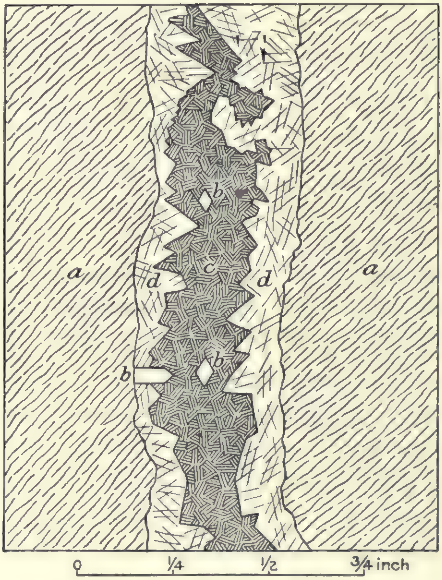


FIG. 151.—Georgetown, Colorado. Colorado Central mine. Veinlet showing deposition first of siderite (d), then galena (c), while a little quartz (b) was contemporaneous with both. Wall rock (a) is gneiss. Does this mean an open fissure, through which water coursed, the solutions changing from iron carbonate solutions to lead sulphide solutions? The carbonate (or quartz) "casing" of a solid sulphide fissure vein occurs so often that it indicates to me (in this figure) a single ore-magma solution which opened and occupied the fissure, from which solution the different minerals were successively precipitated. After J. E. Spurr: Professional Paper 63, U. S. Geol. Surv.; Fig. 95.

the bases in each, although clear and striking, is in the end a relative one. Carbonates, for example, are characteristic, to a minor degree, of the whole sulphide stage; and sulphides occur, to a minor degree, in the carbonate stage.

Fig. 151[8] shows a veinlet in the Colorado Central mine,

[8] J. E. SPURR: *Professional Paper* 63, U. S. Geol. Surv., p. 257.

where in a fissure there has been a first precipitation of brown carbonates and a later deposition of galena. Compare this drawing with that on p. 678,[9] where there has been a first deposition of quartz in a fissure and a later deposition of sulphides (blende, etc.). Also, consider in the case of the gold-quartz veins of California and Australia and the same type elsewhere the characteristic first deposit of siderite, either on the walls or on rock inclusions held in suspension—insignificant in quantity relative to the later quartz, but showing the presence of a small amount of carbonates in the gold-quartz ore magma. Now, just as these Georgetown blende-galena vein magmas had as a minor constituent, besides the metallic sulphides, either silica (usually) or the earthy carbonates or both, so the gold-quartz magma may have this modicum of carbonates, or not. It is immaterial. If it has, it will not only rim the veins, but may impregnate and replace the wall rock, and so, by rimming it, it may sheathe and case off the fissure walls from actual contact with the quartz magma, when it afterward crystallizes. It will be seen that it is a matter of lesser moment—not a guiding characteristic—whether this minor mixture of carbonates is present or not in the gold-quartz magma, or whether in the galena-blende sulphide magma the minor admixture of earthy compounds is silica or carbonates or neither. These are accessory, not primary, features.

Iron, therefore, is a rude metallic barometer-thermometer, in that its combinations, in bulk, indicate successive stages: iron oxides (magnetite and hematite), iron sulphides (pyrite and pyrrhotite), and iron carbonate (siderite). I have suggested above that arsenic similarly constitutes a barometer-thermometer—occurring as a sulpharsenide of iron (arsenopyrite) in the ore magmas, as a sulphide of arsenic (realgar) in the ore-magma residues. Moreover, within the ore magmas, the different sulpharsenides seem to be indicators of a further subdivision of pressure-temperature con-

[9] J. E. Spurr: *Professional Paper* 63, U. S. Geol. Surv., p. 229.

ditions, for while the sulpharsenide of iron is characteristic of the deeper zones of consolidation of the ore magmas (in the siliceous and intermediate vein sequences), minerals like tennantite and proustite (sulpharsenides of copper and silver respectively) are characteristic of a higher zone of the ore magma. Arsenides (as well as sulpharsenides) of copper and silver seem to be characteristic of the relatively higher ore zone in the case of the basic-derived vein sequence; copper arsenides like domeykite and whitneyite, and silver arsenides (huntilite) occurring at Silver Islet, on Lake Superior, and in the Houghton copper mines in Michigan. This lack of adequate sulphur (to form sulpharsenides) is in line with the occurrence of native silver and copper in such deposits as primary minerals.

I suggested in Chapter XI (p. 544) that antimony in the form of sulphide (stibnite) has much the same significance, as a barometer-thermometer mineral, as realgar, being indicative of the ore-magma residue, while the sulphantimonides were characteristic of the ore magma itself. Moreover, it possibly may, in the same way as arsenic, indicate the difference between a lower magmatic vein zone and an upper magmatic vein zone. The sulphantimonide of lead, jamesonite, seems characteristic of the former, and the antimonial minerals corresponding to the upper-zone sulpharsenides—tetrahedrite and pyrargyrite (sulphantimonides of copper and silver respectively)—of the latter. Similarly, in the basic-derived vein sequence, there are (as well as sulpharsenides) antimonides of copper and silver (horsfordite and dyscrasite), whose presence is explained as for the arsenides above noted.

The examples of earthy-mineral veins which I have given above are partly of the deeper vein zones, as at Velardeña and Durango; partly from more elevated zones, as at Inde; and partly from still relatively more elevated zones, as at Silverton. I will now mention the district of Oaxaca, in Mexico, an example of the "Tertiary bonanza type," and, therefore, as at Silverton, formed relatively near the surface.

The deposits are fissure veins in altered andesite. The Providencia and San Carlos veins, which I studied, show the following sequence of distinct openings of the original vein fissure: 1, Dark quartz, with pyrite, some little galena, zinc blende, and silver sulphides and sulphantimonides. This is the ore vein. This was, however, succeeded by three distinct stages of barren-gangue veins. 2, White quartz, containing very sparse sulphides, but usually barren. This incloses fragments of No. 1. 3, Mixed carbonates. 4, Quartz—dark, cherty, barren.

The Santa Francisca vein, at Oaxaca, when examined, showed the following sequence of fissure-fillings in the compound vein: 1, Barren white quartz. 2, Dark quartz, with pyrite and silver sulphantimonides. This is the ore period. 3, Barren white quartz, with very sparse sulphides. 4, Mixed carbonates. 5, Dark barren quartz. Eliminating No. 1, this sequence is the same as for the Providencia and San Carlos veins; and in a general way conforms with the principles worked out above. The calcite which typically closes the magmatic stage, however, is not here represented. The ore veins here represent the uppermost magmatic metal zone—the silver zone—characterized by sulphantimonides of silver, as at Guanajuato.

At the Peñoles mines, in Durango, Mexico, a very interesting and complex geologic sequence was worked out by myself and assistants, in making a geological examination and map of the district. This is a specially complicated case, but for that reason all the more interesting, and not without its valuable lessons. Ore deposits have the endless individuality of people: there are no two alike, and having once known one thoroughly, we shall never find another just like it. But they may be grouped into races, tribes, and families, just like folks. And although they are individually different, it is because they are composites of numerous factors; but we shall find these factors as wonderfully uniform as are crystals of quartz, in whatever association we find them. The final calcitic veins at Tono-

pah, for example, at Matehuala, at Velardeña, or at Peñoles (where I shall presently describe them), and in dozens of other districts where I could list them, all over North America, are remarkably similar in every respect. They are a constant type recognized by the eye more easily even than by the mind, and eloquent of constant physical and chemical conditions, and consequently of fixed and immutable law, which functions independently of geographic locality. And other vein types are similarly uniform—such as the massive galena-blende fissure vein, often fringed with a border of comb-quartz (p. 677).

The oldest exposed formation in the Peñoles district is that immensely thick Cretaceous limestone-shale series which covers all this part of Mexico. It has been intruded by a (hornblende) diorite body which trends east-northeast, with a lenticular shape, and is at most a mile wide. This diorite shows much internal differentiation, so that some portions are very rich in hornblende, others in feldspar, etc. Near the diorite, intruded limestone has been altered to lime silicates—pyroxene, some garnet, and vesuvianite—but no sulphides.

The ores occupy a very definite belt of parallel fissure veins, this belt being two and a half miles long, and 1,500 to 2,000 feet wide. (Fig. 152.) (I have mentioned them in considering fissure veins, in Chapter XVI, p. 733.) The first ore occurred, at a period very distinctly later than the lime-silicates period, as fissure veins in a broad fault zone in limestone, in general following one of the long sides of the diorite intrusive. The ore contains pyrite, arsenopyrite, argentiferous galena, blende, and a little chalcopyrite, with a quartz gangue; so it represents a magmatically telescoped vein of the deeper vein zones—a mixture, principally, of the arsenopyrite and galena-blende elements of typical separate ore magmas—but is not, so far, a compound vein. The Jesus Maria is the principal vein of this type.

A considerable interval of time elapsed, after the infilling of the Jesus Maria sulphide ore vein, before renewed fault-

ing took place along the same zone of weakness, and then rich silver-quartz veins were injected, containing, besides grayish quartz, also argentite, argentiferous tetrahedrite,

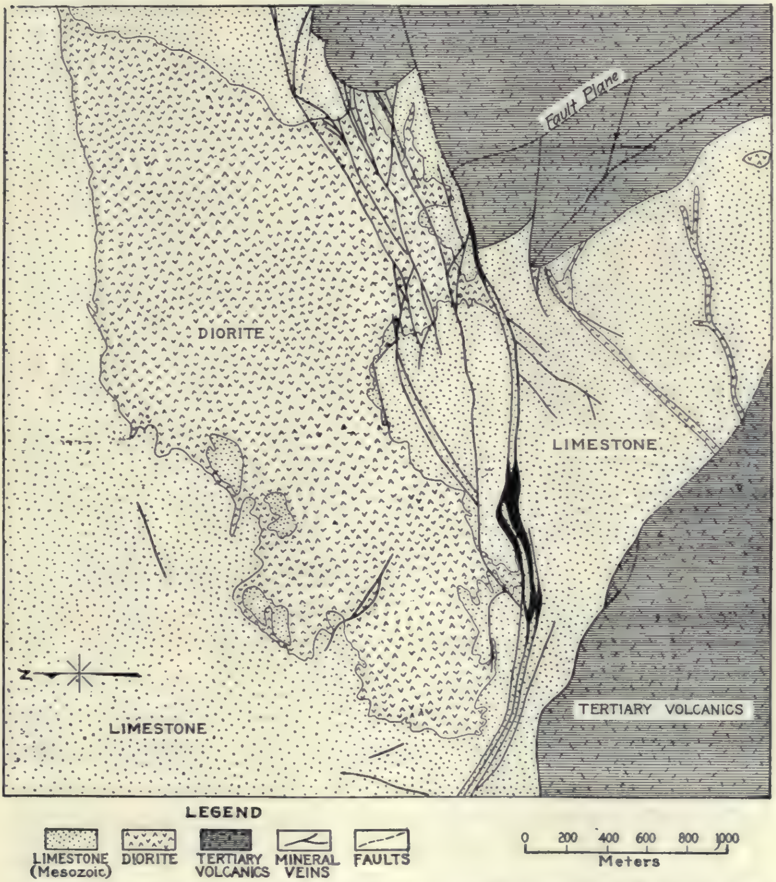


FIG. 152.—Peñoles, Durango, Mexico. The great Peñoles vein zone. The veins occupy a zone of recurrent fault movement. From map by G. H. Garrey, J. V. Lewis, and M. H. Hayward, under supervision of J. E. Spurr, 1909.

stephanite, and pyrite. The principal vein of this stage is the San Rafael. These veins physically are of the linked type, characteristic of Tertiary bonanza veins found close to the surface; chemically, and magmatically, they are of the uppermost magmatic ore type—the principal silver

zone, like the veins I have just described at Oaxaca, which are also, by the way, of the linked type.

Erosion (which had certainly been very active and long between the arsenopyrite-galena-blende veins and the silver-quartz veins) was also extensive after the latter, exposing them at the surface. They were then covered by volcanic outbursts—a series of flows and explosions which piled up lavas and debris one thousand feet thick, all of rhyolitic or alaskitic (tordrillite) lava, coming from a volcano whose neck is now laid bare by subsequent erosion. After the volcanic outburst, faulting was renewed, in part along the planes of the pre-existing silver-quartz veins; and along the renewed fissures thus made, barren-gangue veins were formed. When the new fissures took place along the earlier silver-bearing ore veins, the result was that type of compound vein so often found in mining, where the ore-bearing layers or segments are mussed up in all degrees by the violent influx of the later vein. This is an elementary feature of practical geology that few miners understand; and no miner can afford not to understand this simple and easily understood fact of a compound vein—what constitutes the ore-bearing segments, how to follow them, and not to wander off after any false gods in the way of barren-vein elements. It is a type of compound vein that shows the indifference of Nature to man's needs or ease. Having made a good and rich fissure vein, she spoils it by subsequent barren-vein injections; sometimes spoils it absolutely, in spite of the wise geologist, for the subsequent barren filling raises the amount of rock to be explored, drifted in, and handled, even with the most intelligent mining, so that business thrift may often determine to let it stay in the ground. To the miner, and I fear to some geologists, this compound vein—the San Rafael—appears like a vein, and nothing more.

> "A primrose by a river's brim
> A yellow primrose was to him,
> And it was nothing more."

Yet between the ore-bearing portion and the barren portions of this vein, many millenniums of erosion, and after that the piling up of a thousand feet of volcanic material, intervened. And how much intervened between the earliest vein deposition—the galena-blende-arsenopyrite-cupriferous pyrite vein—and the latest—the barren-gangue veins which split the silver-bearing vein? Enough so that erosion planed down to the upper part of the zone of differentiation in the diorite. No way of measuring that exactly, so far as I know, but it certainly means the removal of a vast overlying column. From general knowledge, I would hardly estimate the height of this column as less than 10,000 feet; and at the rate of erosion assumed in Chapter IX (p. 414) of one foot in 5,000 years, this required 50,000,000 years. This would put the data of the diorite intrusion back into the beginning of the Tertiary, according to Barrell's time scale (p. 396), which seems reasonable in view of all the collateral geology of this part of Mexico, for these earlier ore deposits seem to belong to the general late Cretaceous early Tertiary metallogenic epoch (p. 197). According to my theory, then (p. 841), the removal of this, say, 10,000 feet of overburden (or more), penetrating downward to the upper part of the original zone of differentiation in the diorite intrusion, finally unbalanced the pressure on the static magma in depth, and a new cycle of igneous activity and ore deposition—after millions of years—was initiated, marked at Peñoles, first by the silver-bearing veins, second by the rhyolite eruption, and third by the barren-gangue veins.

These barren fissure-vein fillings at Peñoles are of two chief types—an earlier type of white, frequently chalcedonic quartz, and a later type of calcite, combined with iron and manganese carbonates. The earthy carbonate stages, it will be noted, are not separated as in the cases I have mentioned last above—they are magmatically telescoped, and deposited together. The quartz, which precedes the carbonate stage as it does at Oaxaca and Matehuala, is, how-

ever, often split into successive substages of vein-filling, the first of white quartz, the second of dark quartz carrying locally stibnite and barite, and a third of reddish porous quartz with some carbonates, the last evidently presaging the subsequent earthy carbonate fissure-filling.

The fault-fissuring continued after all the vein-filling, but these last fissures are unfilled and uncemented, showing the extraordinary and magmatic origin of even the barren quartz veins and the carbonate veins. After the calcite veins were formed—abundant and wide, bold fissure veins—the vein history was closed, and from that period, immensely remote as measured with our insectlike measures of time, to the present, no fissure-filling, no beginning, even, of fissure-filling, has taken place. These are, of course, ordinary fault fissures, such as those with which every reader familiar with mines and veins and faults is well acquainted. They are not yawning chasms with fissure walls parallel and several feet apart, into which a pebble may rattle and rebound from side to side till it bounds beyond the hearing, and never finds bottom. The sides are close-pressed together, but the rock is broken and sheeted, and often ground up. The rock is cracked and split: the continuity of its texture is broken—it becomes weak and open to invasion along such a plane. But compare it with the veins which have repeatedly formed along similar fault planes in the past—they certainly do occupy such a yawning fissure; for they have clean-cut sharp walls, and several feet of pure vein filling that has occupied an open space, and has never by any chance formed by replacement. I am speaking of these compound veins at Peñoles. How did the fissure, which they filled, form? The veins formed it—the vein solutions forced it apart, flowed into it, kept the walls apart till they crystallized—intruded, in short. And these statements are as true of all the different successive barren veins here as they are of the ore vein.

To illustrate our study further, I will introduce a drawing I made of a breast of a drift on the Providencia vein

(Fig. 153)—not the same Providencia as I spoke of at Oaxaca but the Providencia vein at Peñoles. There are Providencia veins in nearly every district in Mexico. The Mexican believes in Providence. Note the history of this fine six-foot-wide regular fissure vein. The walls are of shale, which has been silicified. Therefore these were not entirely dry vein magmas, evidently: they exuded aqueous solutions—water—when they crystallized.

1: The first vein was the ore-vein stage—not a pronounced open-fissure filling here at least, but many gray stringers of quartz making a network in the silicified shale —yet a well-defined, well-demarked vein. 2: This vein was split down the center and a fissure twice as wide as the old vein was infilled with dense white quartz, like broken stone-china (the kind of quartz I have described at Aurora—see p. 687). Note the number, shape, and position of the fragments of the ore-bearing vein—of No. 1. They are isolated and without support, distinct and clear-cut, angular. They floated free in the liquid solution which crystallized as vein No. 2, and which crystallized much as it had come in, apparently, for there is no banding—it was a simultaneous crystallization of a homogeneous mass. Yet in other parts of the mine this same stage of dense white quartz is often beautifully banded, showing rhythmic deposition. 3: No. 2 vein was split open along its hanging wall, where this wall came into contact with the hanging-wall slab of the cleft No. 1 vein, and along this new fissure there was infilled material which crystallized as translucent quartz, often comby, which intrudes in detail, as little tongues, the No. 2 quartz. This No. 3 quartz also contains isolated inclusions of the No. 1 vein, which again must have floated free in the solution, in spite of the frequently comby structure with which the solution crystallized. There is not much of this No. 3 vein left in the section, for there was another splitting, and a wide vein of coarse calcite (4) was infilled along very much the same plane. The carbonate (chiefly lime) solution left in place, as the draw-

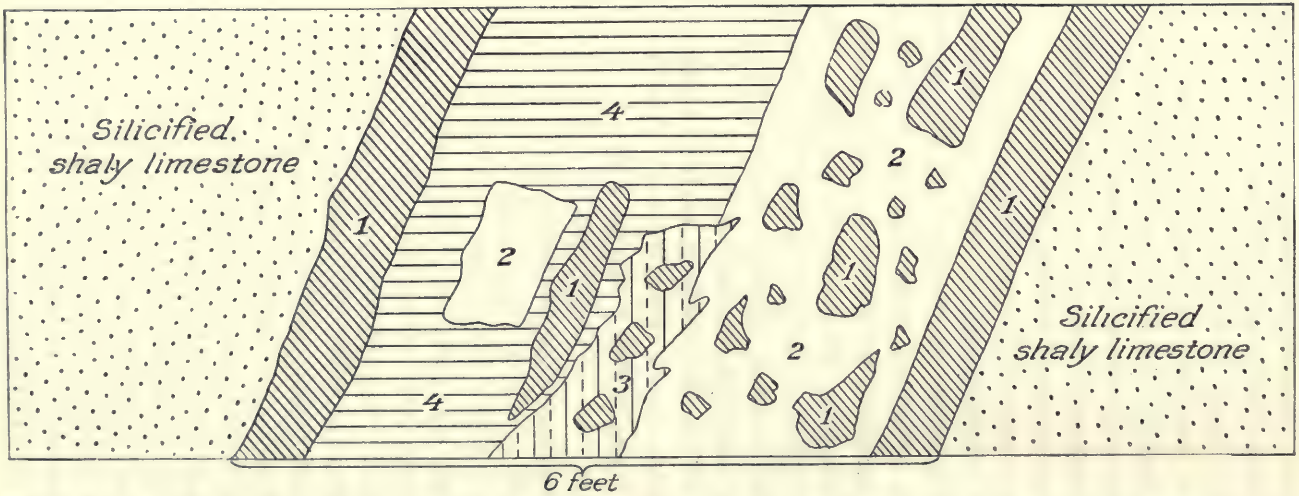


Fig. 153.—Peñoles, Durango, Mexico. Sketch of breast of Providencia vein. This illustrates successive periods of fissure-vein filling, making the present compound vein. 1, First-period quartz, gray, network of stringers in jasperoid; 2, dense vein-quartz, of color and texture like porcelain; includes many angular isolated fragments of 1; 3, translucent quartz, often comby; contains isolated fragments of 1 and has an intrusive contact into 2, as shown; 4, coarse calcite vein, which incloses isolated blocks of 1 and 2, and has an intrusive contact against 2 and 3. Shows ability of quartz and calcite magmas, at all these periods, to carry along and support free, angular included blocks. The intrusive and fragment-supporting characters are then much like those of igneous dikes. By J. E. Spurr.

ing shows, only a remnant of the immediately preceding No. 3 vein. The rest it has evidently torn away and carried out of the field of the section. But it has brought up (I take it, up) from a point outside of the field of the section (for they do not match anything in the section exposed), a slab of No. 1 vein, and a rectangular block of No. 2 vein, each having broken according to its nature—the reticulated veins in silicified shale (No. 1), slabby, the dense homogeneous quartz (No. 2), blocky; while the ragged contact outline of the ruptured No. 3 quartz also shows a third characteristic type of granular quartz breaking under strain. Again, in this final magmatic stage of earthy carbonate solutions (which crystallized as calcite chiefly) the ruptured blocks which were brought up floated free and unsupported.

Here once more we are confronted with the same evidence as at Velardeña (Terneras vein, p. 798), at Tonopah (p. 802), and elsewhere; that up to and including the last magmatic stage of veins, which is the calcite stage, the ore solution was in many cases capable of holding, suspended and isolated, heavy blocks of inclusions. The only other possible theory—that of expansion of the vein in crystallization—is ruled out here as at Velardeña, because the inclusions plainly do not belong to the old walls—they have been brought in from somewhere else. Therefore, they have been transported in suspension, quite in the way that a rock magma may tear out, pick up, and carry along inclusions. In this case there is little difference of specific gravity in the different vein stages, although they are all so distinct in appearance, and, therefore, the added striking evidence which we have at Velardeña and Georgetown (p. 140) of the suspension of heavier inclusions in a lighter medium, does not have to be reckoned with here. But the conclusion is plain enough without this—that the ore solutions, at each and every stage of the last three stages, were so stiff and viscous that they supported quartz blocks in suspension. I have stated this conclusion repeatedly before; but I am now

moved to add another deduction, good for all these cases. The consolidation of this viscous (gelatinous) intruded solution must have been swift. Even in tar, a stone will gradually sink, and find a resting place, or a cork will work its way up. *Hardening of the jelly must have swiftly followed intrusion.* Faced intelligently and frankly, we shall have hard work to explain the phenomena of the (latest) calcitic fissure veins, in many places, without granting: 1, forcible and violent injection; 2, in a viscous condition; 3, swift consolidation after intrusion. And these are all conditions which we have long granted for igneous dikes—but not for mineral veins.

Yet, as I have above noted, these vein solutions were not entirely dry—not apparently as dry as some I have described, such as that at the Potosi mine, at Santa Eulalia. The limestones are silicified—altered to "jasperoid"—in their vicinity. Therefore, when they consolidated, some waters were excluded, which penetrated and replaced the lime-shale wall rocks, a thing which the viscous ore-vein solutions themselves did not do. This was their way of contact metamorphism (metasomatism)—indeed, when these barren post-metal-stage earthy-mineral veins crystallized, they did exactly what an igneous magma does—they excluded, on crystallization, water, which entered into and replaced the wall rock. The analogy between the quartz or calcite vein which closes the last act of the magmatic drama is, therefore, surprisingly like that of the first—the rock magma—as to intrusion, viscosity, quick consolidation, and separation out of water which metasomatizes the wall rocks.

May I add that in my case the theory above expounded has lagged years behind the observations on which I base it—and that the drawings were made years ago, carefully but without comprehension?

One other feature in my drawing of the Providencia vein should not be overlooked, as I study it. Note the orientation of the inclusions with their long axes parallel to the

walls. This fact, of course, by itself disposes of the old theory of the "rubble-filled fissure" which I am sorry to say I blithely recorded for years as an explanation of these inclusions in veins. It does clearly signify the direction of pressure at the time these included blocks came to rest—that at that time the pressure was not that of the moving current in the earthy gel which encompassed them, but was perpendicular to the fissure walls—was in fact the pressure of these fissure walls, on the stagnant and hardening gel. And, therefore, it records very slightly different conditions from those shown in my drawing of one locality in the Griffith vein at Georgetown, Colorado, Fig. 26 (p. 140). This section of the Griffith vein shows vertical pressure as the dominant one when the vein froze, but whether due to the vein-magma pressure below, or the weight of the vein-magma column above, I cannot say. But I think this latter orientation will be found to be the exception rather than the rule, and that in general inclusions will register the wall pressure as the vein froze, as the chief pressure, as they do at Peñoles. However, Fig. 20, illustrating a vein in the Mendota mine, in Georgetown, which figure is a sketch on a horizontal plane, registers a lateral pressure, certainly due to lateral flow.

Some other observations as to these barren lodes are of interest. The barren quartz, which succeeded the ore-bearing quartz, in many places in the mine workings shows primary pyrargyrite (ruby silver). The sporadic nature of these occurrences (which have no economic importance) and their close contiguity to the real ore indicate almost beyond doubt that the barren-quartz solutions dissolved silver from the quartz ore which they shattered, and that it then recrystallized. The original silver minerals, however, were argentite, argentiferous tetrahedrite, stephanite, and pyrite, but not pyrargyrite. For the still later barren calcite veins the proof of this slight local activity in dissolving metals is still more clear. In the ore pile of the mine excellent examples were found where such a calcite veinlet had

split and faulted an earlier veinlet of quartz carrying silver sulphides; and had dissolved and reprecipitated some of the sulphides—precipitated them almost entirely in the form of pyrargyrite (ruby silver), so far as seen. Although tetrahedrite is conspicuous in the real ore, it was not observed in the subsequent "reincarnation" in the barren-gangue veins.

Another mineral which occurs sporadically in this later barren quartz which immediately followed the ore period is stibnite, locally fairly plentiful, though not of economic importance; and it was not noted in the early ore-bearing veins. The stibnite, like the barren quartz, is post-volcanic, and occurs along faults in the volcanic rocks which cap the ore-bearing veins.

The sparse occurrence of stibnite in this barren quartz suggests that its origin is the same as the evident origin of the pyrargyrite which occurs in the same quartz in the same manner—that it is derived from solution of the sulphantimonides of the original ore. This conclusion as to stibnite corresponds admirably with the theoretical conclusions which I have drawn in Chapter XI, and also earlier in the present chapter, to the effect that stibnite and realgar are characteristic of the late magmatic solutions, subsequent to the main ore stages, and that sulphantimonides and sulpharsenides are characteristic of the main ore stages. The stibnite in this Peñoles vein, which immediately succeeds the ore vein, matches the realgar in the Caldas vein at Velardeña, which also immediately succeeds the ore vein.

The occurrence of pyrargyrite here at Peñoles puts it, here at least, in the same class as stibnite here and realgar at Velardeña—as characteristic of the post-ore residues, and derived from the final silver sulphide stage of the ore magma proper by petty leaching and redeposition. In the case of realgar and stibnite, the chemical combination of arsenic and antimony in the earthy-vein magma stages is a characteristic one—that of the pure sulphide, which probably does not occur in the ore-magma sequence proper, in

the case of arsenic at least. But in the case of silver, the ore-magma minerals here at Peñoles are argentiferous tetrahedrite (copper-silver sulphantimonide), stephanite (silver sulphantimonide) and argentite (silver sulphide). Nevertheless, the subsequent pyrargyrite is also a silver sulphantimonide, and even an inspection of the relative proportion of the elements in the different minerals gives no clew to the reason why the particular sulphantimonide pyrargyrite seems characteristic of lower pressure-temperature conditions than the other silver sulphantimonides or sulphides. It is true that pyrargyrite (with which we may group, in general, its companion mineral, proustite—silver sulpharsenide—and refer to them both by their familiar name of ruby silver) is as a rule a stranger to stibnite and realgar deposits and, therefore, is not so persistent beyond the ore-magma zone as they are. It is possible, however, considering the occurrences of ruby silver, and considering also its close association always with the original ore-magma silver minerals, that it is always secondary to these latter, and due to their dissolution and reprecipitation by a different type of solutions and under different pressure-temperature conditions: by the analogy of arsenopyrite vs. realgar—see p. 811—we may assume that here also the pressure condition is important, and that in the ore magma the pressure is the repressed gaseous-tension pressure, which is lost in the succeeding earthy-vein magma—perhaps by the passing of the temperature below that critical for water, as I have assumed, with the consequent general change from a condition of gaseous tension to that of a gel in the earthy-vein magma, the latter, however, still kept in a state of lesser gaseous pressure by the content of the most persistently gaseous elements, like carbon dioxide. While this secondary derivation seems thus true for the silver in the barren-gangue vein stages, at Peñoles at least, it is not true of arsenic and antimony, which act both as bases and as acids, while silver is always a base. As acids, arsenic and antimony are characteristic of the ore magma, perhaps

exclusively so; as bases—the bases of the arsenic and antimony sulphides—they are characteristic of the post-ore-magma magmatic solutions, and occur so far away from the ore-magma veins, and in such quantity, as to show that these metals, in the form of sulphide, form a real primary residue from the ore magma, and not simply or even in large measure a worked-over or secondary form of original or primary ore-magma minerals, as is the case with silver. The stibnite occurrences at Peñoles contain little or no silver.

Although ruby silver, therefore, is probably not a post-ore-magma primary magmatic mineral, as a secondary mineral derived from the ore-magma primary minerals it is very characteristic and persistent, and moreover forms under a variety of conditions. In this Peñoles mine, for example, I have shown that the different members of the sequence of earthy-magma veins—both the earlier quartz and the later calcite veins—have had this effect of leaching out the silver sulphantimonide and precipitating it as ruby silver, *while they have not leached the copper sulphantimonide.* But further than this, ruby silver is found at Peñoles as a last deposit in geodes, or along cracks, which are later even than these earthy-gangue veins; and indeed this last deposition of "ruby" is possibly the work of ordinary atmospheric cold and descending waters.

Let me recall in this connection my observations at Tonopah in regard to "ruby" silver. In this camp the chief primary mineral is polybasite; and the ruby silver (pyrargyrite) was noted as entirely secondary,[10] always coating crevices cutting the primary ore, together with other secondary sulphides. Some of these sulphides are apparently repeated as both primary and secondary minerals: but not so the ruby silver, which appears invariably secondary. At Tonopah, the ruby silver has certainly, in some cases, been deposited by descending surface waters, since it

[10] J. E. Spurr: *Professional Paper* 42, U. S. Geol. Surv., p. 95.

occurs as a fresh precipitate along cracks in partially oxidized ores.

At Ojuela, some thirty miles from Peñoles,[11] where are the great silver-lead deposits described in Chapter V, there was not, among the many veins which I observed, any of compound nature, showing repeated splitting and fissuring; which is the diametrically opposite condition from that of the Peñoles vein fissure, thirty miles distant, which contains the extreme type of compound vein described above. Now, at Ojuela conditions are excellent for the examination of an extensive vertical section. As seen in section D, Fig. 48, the main shaft and drill hole in the rich ore deposits explores a depth of around 3,500 feet, while above the top of the mine the precipitous limestone scarp rises to the top of the mountain at an angle of nearly 45°, to a further vertical height, of 2,500 or 3,000 feet, so that the whole vertical section is about 6,000 feet. I have before described how the bulk of the ores found in the mine are lead, zinc, arsenic, and some copper. The ores are thoroughly oxidized down to a depth of 1,500 to 2,000 feet, and in this oxidized zone the values are in silver and in lead; in the sulphide zone below, the chief minerals are galena, blende, arsenopyrite, and more or less cupriferous pyrite. With increasing depth in the sulphides, galena plainly decreases, and the pyrite becomes more cupriferous, till in the greatest depths cupriferous pyrite becomes abundant, and the limestone has been altered to lime silicates, as the top of a submerged deep intrusion of alaskite is neared. The nature of the original sulphides now represented by the oxidized orebody is, of course, not certain, but from the frequently rich silver content of these oxidized ores, I think it likely that the principal silver zone was at least partly represented in the upper workings. Here, then, in a vertical depth of 3,500 feet or so, we have a transition from the upper part of the copper-pyrite zone through the arsenopyrite (probably

[11] The reader will please refer back to p. 818, of this chapter, taking up the connection again after my digression to discuss underlying principles.

auriferous) zone, through the blende, then the galena, to the principal silver zone; but the mixtures of sulphides and the gradual though very marked change show a certain amount of "telescoping" of zones, and that, therefore, the whole ore deposition took place at depths not very remote from the surface. In describing these orebodies, I observed that the top of the mine was apparently the top of the ore zone; for, in the steep mountain slope above, the numerous veins in the limestone are of the barren-gangue (earthy) minerals only.

I now wish to add (from my notes) interesting observations made in our minutely careful geological survey. On the top of the limestone mountain the veins are of the fissure type ("stringer-lead type") and are mostly siderite and calcite, with very rarely quartz. Further down on the mountain more quartz appears in these veins, which then become quartz-siderite-calcite veins, and the relative amount of quartz seems to increase in depth. Many of these veins carry stibnite, and, so far as noted, these stibnite-bearing veins are all considerably below the upper part of the mountain, and considerably above the top of the original main sulphide ore zone (lead-silver) outcropping below; that is, they occupy a definite limited vertical zone in this 2,500-foot zone of barren-gangue veins. Occasionally these veins show galena, fluorite, and barite. They carry sometimes a little silver, perhaps more than the stibnite-bearing veins at Peñoles, the maximum being stated at 300 grams per metric ton, which, of course, is not a sufficient grade to make ore.

Here, then, at Ojuela, is a normal vertical sequence, with the barren-gangue vein zone 2,500 feet high, actually lying above the (originally) sulphide ore zone which is 3,500 feet high[12]; and the stibnite in these veins confirms the

[12] Even at Ojuela, however, there are minor effects of the magmatic downward migration of vein zones. The lowest zone of barren or nearly barren veins, which contains contemporaneous barite, fluorite, quartz, and galena, shows later siderite, and still later subordinate calcite.

hypothesis that this antimony sulphide passes into the residue from the sulphide ore magma, and crystallizes in the earthy-gangue vein zone; and thus the same truths are exemplified as are shown at Peñoles by vein compounding—that is, by the veins of the upper vein zone (earthy gangues) through falling temperature forming along fissures opened up in the veins of the lower vein zone (sulphides), and the whole making up a compound vein. Certainly, in a case like Ojuela, therefore, it would be advisable to explore at a great depth (by a long crosscut from the present deep mine workings) those vein zones which are barren or only stibnite-bearing or meagerly galena-bearing (the galena probably being secondary and leached from the sulphide ore deposits below by the residual earthy-gangue magma, like the pyrargyrite at Peñoles), in the hope of finding the main sulphide ore zones in depth. In other districts, however, where there has not been the certain amount of "telescoping" that is here indicated, even this depth of several thousand feet for exploration might not be deep enough to get into the sulphide ore zone.

In the case of these barren-zone fissure veins at Ojuela, in this vertical extent of 2,500 feet of limestone, let us note that these regular fissure veins do here form in limestone walls, indicating a relatively dry ore magma, such as seems to be the case for the Terneras vein, at Velardeña, and elsewhere. Take into consideration the evidence of a viscous or jelly-like condition as derived from the inclusions in this same barren-gangue series at Peñoles, and we are led to infer a corresponding condition at Ojuela to account for the fact that the quartz-siderite-calcite-barite, with inclosed sulphides, did not pass into the limestone as irregular bodies, but instead pierced it as fissure veins of regular strike and dip. We could understand this for the carbonate veins without the assumption of a relatively dry or jelly-like magma, but not for those numerous lower veins in limestone which are mainly of quartz.

The thick limestone formation in which these fissure

veins lie is overlain abruptly by a thick shale series. Typically, if not always, the veins do not persist upward into this shale, but spread out into a sheet of quartz—"mushroom" out, as the local miners put it, beneath the shale, replacing then the limestone. The diorite which follows and is later than these veins has the same habit (Fig. 154).

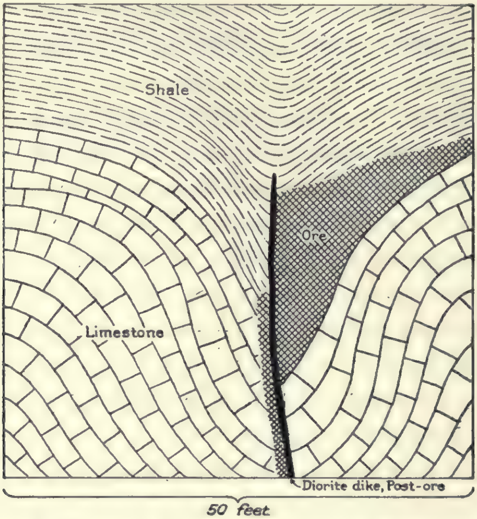


FIG. 154.—Mapimi, Durango, Mexico. Vertical cross-section sketch of San Ramon mine, showing ore deposition beneath shale series, by solutions which ascended along the crushed axis of a syncline. Along this same course ascended a dike of diorite, later than the ore-magma ascension. Neither diorite nor ore passes beyond the lower layer of shales. Ore is galena, cupriferous pyrite, quartz, barite, etc.

It is an additional problem, the solution of which is not yet suggested, why, if realgar and stibnite are alike derived from the residue of ore-magma solutions which contain both arsenic and antimony, we do not get always realgar and stibnite together in these residual-magma veins. Sometimes we do, as at Manhattan, in Nevada; but at Ojuela, where there is much arsenopyrite in the low-lying sulphide ores, the overlying barren-gangue ores carry stibnite, but not realgar. It may be that realgar is more characteristic of the residual magmatic hot water and vapor

zone than of the residual barren-gangue vein zone, such as we have at Ojuela and Peñoles. This is certainly the case with cinnabar, with which realgar is often associated.

Reviewing this chapter, I think that perhaps now I have detected the bottom of the zone of hot-spring waters, and the top of the ore-magma zones. I have shown that the barren quartz and carbonate veins which succeed the sulphide veins in many mineral districts can hardly be regarded as deposited by hot waters such as we see emerging from hot springs; that they were not highly aqueous solutions, but jelly-like solutions. Yet from them, as they crystallized, residual solutions were given off, so thin and dilute that they passed with ease through the wall rock, altering the limestone to silica (jasperoid). It is, I think, safe to assume that these were essentially hot waters—of magmatic origin, surely, yet not essentially dissimilar from the hot springs which emerge at the surface. The magmatic calcite stage, then, is the last of the magmas which are highly concentrated or supersaturated (while they vary in water content from aqueous and gaseous to relatively dry); when this calcite magma freezes, we have residual hot magmatic waters. And just such hot magmatic waters are given off from every stage or member of the magmatic sequence, from igneous rock to calcite veins, when each consolidates. This water (principally) thus disengaged or expelled from every magma (whether rock magma, ore magma, or earthy-gangue magma, these being the three main divisions) is not to be confused with the ore magmas and their subsequent earthy-gangue magmas which result from differentiation from the general magma, so that in a way all are igneous types. The hot residual waters are not, in this sense, due to the differentiation of magmas: they are a component of all types of magmas and act as a solvent in all. The freezing or consolidation of any type of magma means the elimination of the water and other volatile and gaseous elements, assuredly carrying mineral matter in solution, but chiefly carrying easily soluble elements,

like the alkalies. These hot waters represent apparently a relatively dilute solution even of these most soluble elements, and they probably are poor in metallic elements, just as they are when they emerge on the surface as hot springs. This is probably usually true even of arsenic and antimony, which these hot springs do deposit in small quantity; for the abundance of hot springs, and the rarity of their containing these metals, as I before pointed out, indicates that only hot waters derived in a certain exceptional way are metalliferous. Evidently this certain way is that the metalliferous waters containing arsenic and antimony are those residual from those ore magmas which contain strong concentrations of these metals. Hot waters derived from the consolidation of the ordinary type of igneous rocks, therefore, are typically not metalliferous, and do not form ore deposits; and thus finally we begin to understand why all igneous rocks are not the cause and the associate of ore deposits, and, further, why ore deposits are not invariably or even usually associated with particular types of igneous rock—in other words, why the igneous rock guide and criterion fails; while the converse is true, that where ore deposits do occur there are apt to be igneous rocks—which is to say, other and distinct types of magmatic injections—near by. But while the more ordinary igneous rocks represent a common type, a mixture or undifferentiated mass, the ore magmas are the highly differentiated type, which may originate from rock magmas of different composition, given only the critical and sustained conditions necessary for complete segregation.

Evidently, also, the source or point of departure upward, of hot waters or hot springs, varies enormously. For the ordinary type of hot spring which is not metalliferous, which is given off from the cooling rock, its source will depend simply upon the depth of the rock undergoing rapid refrigeration, and that, as we know, may be very deep—indeed, the maximum depth no one has attempted to demonstrate. Where igneous rocks appear on the surface,

as at volcanoes, the hot spring will plainly begin as soon as the temperature of the most superficial shell of rock is cool enough to liquefy the water vapors which in the earlier stages are given off from fumaroles; and with the downward refrigeration of the rock the source of the hot waters will sink as long as there is any rock in the magma column which is undergoing refrigeration, and until the deep-lying zone of differentiation is reached, where the refrigeration or consolidation is so slow that the aqueous contents are not simply eliminated *en masse,* but segregate along with other elements of the magma (which they aid in segregation), and so find their way into various submagmas—more or less highly differentiated rock-magma types, as well as more or less highly differentiated pegmatite and ore magmas—which, when collected, severally migrate upward to a zone of quick refrigeration; and at this zone, the water is forcibly eliminated, as in the case of those undifferentiated or partly differentiated rock magmas which have traveled the same road. That is to say, the zone of the elimination of hot waters on refrigeration of rock or ore magmas overlies the zone of differentiation, where the hot waters are retained in the magma, and serve as one of the agents of differentiation. Naturally, there will be no sharp line of demarcation between these zones, but one will pass down into the other gradually.

Fumaroles, therefore, may be properly and to advantage visualized as vaporized hot springs; and, conversely, hot springs as cooled fumaroles. Neither represents the products of differentiation; neither represents the principal ore-depositing fluids, the ore magmas. For the latter we do not have, nor ever shall have, any visual corroboration, any more than we have of granites or of rock differentiation.

This conception of the zone of refrigeration without differentiation, overlying the deep-seated zone of differentiation in any magma column which has pushed far up, even as far as the surface, harmonizes with the conclusion separately worked out that differentiation depends upon

upward migration into the zone of slow consolidation. Therefore, there are indeed in any such magma column three zones—the uppermost zone of swift refrigeration without differentiation, the middle zone of slow refrigeration with differentiation, and the lowest zone, of no refrigeration, where the magma remains changeless (at least so it appears), though fluid.

This hypothesis of downward extension, in any intrusive magma column, of the zone of no differentiation into the zone of differentiation, implies that differentiation below is going on at the same time as consolidation without differentiation above. By all our ordinary conceptions the differentiation should be a much slower process. But the fact, which is general and characteristic, that veins are formed in the first fissures that originate in or near a given intrusive rock, by the settling and adjustment movements consequent upon its consolidation, suggests that the differentiation into ore magmas is frequently completed in the deep-seated middle magma zone of differentiation before and during the period of downward refrigeration of the magma column to the extent necessitating this first slight adjustment which results in systematic rifts, cracks, and fissures of slight displacement. The fact that the later movements of adjustment, which result in pronounced faults, are generally barren, taken together with the typical formation of veins in the first-formed slight fissures, also indicates, it occurs to me, that ore deposition in general takes place only while the rocks are still hot; and this confirms, in my mind, my previous deductions that the consolidation of all ore magmas takes place at a relatively high temperature. I have suggested, simply as something to hang one's thought upon, but without any warrant for the exact figure, the temperature of 365° C. or higher for all the true ore-magma stages, and a somewhat lower temperature—may we hazard the rough figure of down to, let us say, 300°—for the barren-gangue veins. Below this will come the hot-spring temperatures.

This conclusion that ore deposits, formed by the typical ore magmas, and representing all the metallic zones, are formed only in hot rocks, deserves to be repeated and dwelt on a little; it explains many things more clearly. It throws light on one of the reasons why ore deposits are closely associated with igneous rocks, for these at a certain early stage of consolidation have furnished the requisite temperature range for the consolidation of the ore magmas. It emphasizes again the conclusion that those ore deposits formed in and near Tertiary lavas, very close to the surface, were intruded at a certain early stage of cooling, after the extrusion of the lavas. It shows very clearly why veins are formed in the first slight cracks and fissures of an igneous rock and near the igneous rock, for these first fissures represent the critical early stage of cooling and adjustment which is the temperature stage for ore-magma consolidation; and why the subsequent fissures and graver faults would normally be typically barren of ore deposition in any case, as happening at a stage of refrigeration too great to permit the ore magmas to ascend so high, even if they are still active in depth.

The same considerations probably apply to small igneous dikes as well as they do to mineral veins and veindikes. The fact that dikes are characteristically intruded into fissures of slight displacement, the first cooling and adjustment fissures after the general intrusion or accompanying it, suggests that they can (as very small dikes) penetrate a hot rock only. The frequent close connection between dikes and veins is thus seen to have still another reason, and especially those occasional cases where dikes and veins alternately fill the same fissure. And the rarity with which a dike has occupied a considerable fault fissure corresponds with the habit of mineral veins, and for the same reason—at this advanced stage of magma adjustment the rocks are ordinarily (but not, of course, always) too cold for the far intrusion of narrow dikes. Of course, *dike temperature is hotter than veindike temperature, so that a vein normally*

follows a dike: in the occasional cases where a dike follows a vein along the same fissure, or otherwise intrudes a vein, a revival of higher temperature, due to a magma-surge below, is perhaps indicated; but each (dike or vein), in the typical instance, represents hotter temperatures than obtain at any succeeding time, after the receding of the heat waves induced by the broader magmatic invasion.

The strengthening of the conception that vein magmas cool only in hot rocks, taken in connection with the fact that copious and sudden ore deposits form within a few hundred feet of the surface, but never slop over at the surface, demonstrates anew that ore magmas cannot exist as such within a few hundred feet of the surface. In the initial stages of cooling, when the lava rocks are very hot, the ore magmas penetrate upward along the first slight fissures; they may be very hot, as is shown by the frequent "telescoped" composition, containing often metals characteristic of the higher-temperature zones: nevertheless, they stop short of the surface, showing that the physical conditions—pressure, and not necessarily temperature—within a few hundred feet of the surface, destroy the coherency and fluidity of the ore magma, and precipitate it. This harmonizes with the assumption that the ore magmas are essentially in a gaseous condition, for these pressure conditions would not so limit the ascent of a simply liquid ore magma, or of simply liquid ore solutions of any kind.

Finally, the essential restriction of all ore deposition, from the highest-temperature to the lowest-temperature zones, to the stage of initial fissuring following a general magma invasion, harmonizes with the belief that the whole temperature range of ore deposition is not very great—all lower, of course, than the temperature range of igneous rocks—but following probably immediately upon the temperature of pegmatite consolidation (say 575° C., p. 263) and extending down to perhaps the critical temperature of water (365° C.), as above assumed. The ore magmas are then the lowest-temperature true magmas, as well as the

most highly differentiated or specialized, and these peculiarities have for long prevented them from being recognized as magmas, and from having their true affiliation with the igneous rocks recognized.

In some cases the igneous rocks in which mineral veins occur are of a fairly extreme type, which indicates that rock differentiation has proceeded far before they were sent up into the crust, as is the case with rhyolites, and alaskites, and, as well, perhaps with the basic rocks like peridotites; and in these cases it is fair to infer that the differentiation which has produced the ore magmas which supply the fissures in these rocks with their subsequent veins has operated not only over the lapse of time between the intrusion and the vein-filling, but, in addition, has had the lapse of time between the surgence or uplift of the chemically static magma in depth to the zone of differentiation above, and the evolving of the alaskite or peridotite (as the case may be) as the result of the occupancy by the original magma of this middle zone. Therefore, these highly differentiated rock magmas and their associated and subsequent ore deposits approach each other more nearly in age than do intermediate rocks and their subsequent ore deposits; and in extreme cases become not far from contemporaneous, or even contemporaneous.

But in very many cases the intrusive rock which is the host-rock for subsequent veins is of an intermediate type—andesite, monzonite, granodiorite, or diorite—a type uniform over large areas—which does not suggest itself in any way as a differentiation product, but which, indeed, on the other hand, does suggest itself as the type of primitive magma from which associated igneous intrusions—rhyolite, and basalt, alaskite and diabase—have been derived by differentiation.

This rock differentiation, it then appears very decidedly, is not necessarily an earlier or a preliminary process, in the zone of differentiation, to that of the differentiation of the ore magmas, for the intrusions of the latter do not regularly

follow those of the former, but occur in varying relations to them, now earlier, now later, so that the net result is that they are to be regarded as partly simultaneous; and this demonstrates that in such a magma column as I am discussing, rock differentiation and ore differentiation take place simultaneously, and are indeed products of one and the same process. The examples which can be cited to demonstrate this are numerous, for in many mining districts some extreme type of differentiated rock comes lagging along, in its intrusion, after the mineral veins have arrived.

Therefore, it would appear that the space of time for differentiation—for the preparation in the zone of differentiation of the ore-magma solutions (and also of the simultaneous splitting of the magma into differentiated types of rock magma)—is geologically brief, accompanying systematically refrigeration or consolidation of the horizontal section of the overlying magma column in which the veins are found.

The fact that once the relatively swift cycle of successive vein sequences is run, terminating, as we have seen (in any given horizontal section), typically in calcite fissure veins, the intrusive and mineralizing activity is dead, even in cases where there is evidence (such as the intrusion of later dikes) of continued relatively elevated temperatures, suggests another possible deduction. As the mind conceives of the consolidation of the differentiation zone, it naturally assumes that, if this is due to refrigeration, the differentiation zone would gradually work down lower, and we should have a continually renewed crop of veins and highly differentiated dikes. We do not have evidence of this: the differentiation zone probably does not work continuously lower. For each intrusive or surgent act or episode, it results that there is just one fixed zone or vertical belt of differentiation.

In connection with this we must consider my representations that magma differentiation cannot be mainly due to fractional crystallization; that it takes place in still fluid

magmas, by a process which we can apprehend, but do not understand as a problem of physical chemistry, at a certain temperature-pressure zone attained by intrusion (just as the still higher and overlying rapidly consolidating zone is thus attained by intrusion); that this process involves an astonishingly free migration and separation of the different molecules in the still fluid magma, which activity I have conveniently assumed as due to differential gaseous tension, since the usual movement seems to be from the body of the magma toward the walls, after the manner in which gaseous tension would operate. Whether this differential activity of the molecules (which expresses itself in marginal and concentric zones in deep-seated magmas, which through erosion we are in some places now privileged to view, and which differential activity must be regarded as characteristic of a transitional stage between the inactive fluid magma solutions in depth and the extremely active magma solutions higher up whose activity results in more abrupt solidification or freezing) always ends in solidification, must I think be open to question; it would indeed seem more logical, in view of the facts, that at the bottom of every given differentiation zone there is a transition zone of the fluid magma, where the segregating activity of the molecules, owing to increased pressure, grows less and less, till the permanently static though fluid magma below is reached (Fig. 155).

Many intrusive masses of igneous rock, of course, do not extend far above the zone of differentiation; some, again, do not get above the zone of differentiation at all, of which latter type the domical intrusions described by Duparc (p. 569), in connection with the origin of platinum in Russia, constitute an example. Some of these deeper intrusions are, as we know, eroded below the zone of vein formation or consolidation. In some cases, however, it is noted that the uppermost part of the zone of differentiation (exposed by erosion) is higher than the zone whence ore magmas have sprung; for fissure veins and other deposits

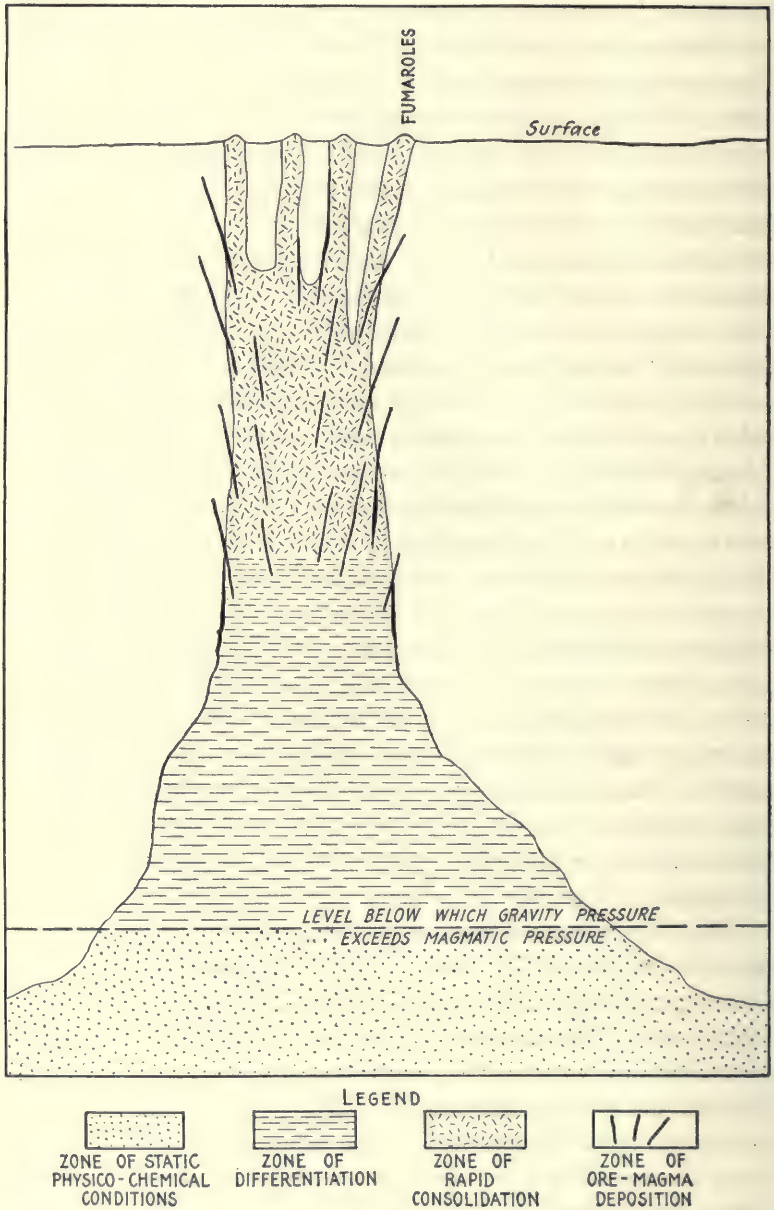


FIG. 155.—Ideal diagram to show relations of the three magmatic zones established by the act of intrusion: the zone of rapid consolidation, the zone of magma differentiation, and the lowest zone of no change; also, the relative position of magmatic ore veins.

coming from below have formed in these slightly differentiated intrusions, which act as host-rocks. Such, for example, is the case at Matehuala, at Velardeña, at Descubridora (p. 647), at Peñoles, and at other places. And this shows that descending refrigeration does in some cases finally affect the zone of differentiation, in its upper part at least, and so arrests differentiation; but it does not follow that the lower part of the zone is simultaneously lowered. For a certain limited vertical range only, it is likely that the central locus of ore-magma differentiation may migrate downward with refrigeration, for we find frequently, even almost typically, an earlier higher-temperature type of ore deposit, on which has later been superimposed, with falling temperature, a lower-temperature ore deposit which, at the time of the formation of the first-period vein, must have been deposited vertically far above; and this vein sequence, indicating a certain span of continuation of the sending upward of ore magmas, and perhaps also of the activity of magma differentiation, may in some cases be followed, as I have mentioned, down into the uppermost part of the magma-differentiation zone.

We can perhaps justify the putting forth of the hypothesis that at a certain depth the pressure, due to the weight of the overlying crust, is so great as to overbalance and render inert the pressure of the gaseous tension of the magma; and that this is the bottom of the zone of differentiation, above which the lower limit of complete consolidation may lie at greatly varying distances. Long-continued and deep erosion, however, removing substantial layers of the overburden, should eventually create an inversion of strain-balance, whereby the pent-up and compressed-gaseous-tension strain of the static magma gradually becomes greater than the pressure of the overburden, till rupture and upward migration of the static magma takes place, and a new cycle of intrusion, rock and ore differentiation, and ore deposition supervenes. This profound erosion thus has a twofold effect in affecting magma migration: first in causing the setting in of the

magmatic undertow which under the laws of isostasy (equilibrium) shall tend to compensate, in a thickened magmatic foundation, for the carrying away of the upper layers of the crust; and second in determining the eventual upward intrusion of the underlying static magma already present.

The rules, or rather lack of rules, as to the depth below surface of the point of origin of hot magmatic waters derived from the rapid refrigeration of rock magmas will, naturally, apply also to those hot springs which are derived from the consolidation of specially metalliferous magmas, or ore magmas, and which, therefore, may contain arsenic and antimony, mercury and probably on occasion gold also, as we have seen. While such metalliferous hot waters are probably residual from each stage of ore-magma consolidation, the major period is probably that succeeding the last metalliferous stage of deposition of the ore magma, which is the silver-bearing stage, exhibited in its purity at Peñoles, and mingled or telescoped with earlier stages at Velardeña. This silver-bearing stage of the magma may arrive quite close to the surface, as at Divide (p. 552), or it may consolidate further down, which is the case at Peñoles, and more markedly at Velardeña, where all metal consolidation took place at some depth; and, therefore, the point of origin of such residual metalliferous hot-spring waters may be shallow or deep. The fact that mercury deposits have been followed down several thousand feet is another bit of evidence. It has been remarked that such mercury deposits show no disposition to change into ordinary mineral veins: and it will be seen, on the assumptions I advance, that they will not and do not form any such transition; and that the passage between the ore magmas of the ordinary metalliferous veins and the rock magmas is a more gradual one than between the ore magmas (and their final stage, the earthy-mineral gangue veins) and even the metalliferous hot-spring waters.

CHAPTER XIX

The Sand or Breccia Dike

This chapter describes as an occasional magmatic phase, dikes of mud, which, cemented by silica, now form dikes of "conglomerate" or of "breccia" or of "sandstone." These dikes occur between stages of metalliferous veindikes, and are believed to be due to waters and gases residual from the ore magmas.

THERE IS ONE PHENOMENON of magmatic vein-filling—one irregular stage of magmatic vein formation—which it will pay us to consider separately. In the Pony Express mine, near Ouray, Colorado, I have earlier mentioned[1] an inverted normal magmatic vein sequence: 1. High-grade silver ore (sulphides and sulphantimonides), with a gangue of barite, mixed earthy carbonates and some quartz—evidently the topmost, principal silver stage, of the normal sequence; 2, blende, pyrite, and slightly argentiferous galena—the principal lead-zinc zone (Fig. 156).

This inversion of the natural order of these same two metallic epochs, I pointed out, is also noted at Aspen; and elsewhere (p. 680). I have drawn the inference that these inversions (signifying rising temperature) denoted a surgence, beneath, of a magmatic protuberance during the period of vein injections. But between these two normal (though inverted in order) phase injections at the Pony Express, there occurred an extraordinary event, a number not down on the regular program, which I shall now describe for the Bachelor vein. After the first silver-barite filling of the chief vein—the Bachelor vein—the vein fissure was split wide open again, and was filled with an upwelling mass of mud, derived from the detritus of the underlying

[1] P. 679.

formations. This upwelling mass was probably dammed back, in its ascent along the fissure, by shale beds (the country rock shows an alternation of nearly horizontal sandstones and shales) which afforded no opening sufficient for the passage of a mass of this sort. With accumulating upward pressure, the mass burst through the shale, and the soft shale fragments were borne along, and now are very characteristic of the dike, being arranged in the sandy matrix with their long axes parallel to the walls. In the sandy matrix the grains are rounded.

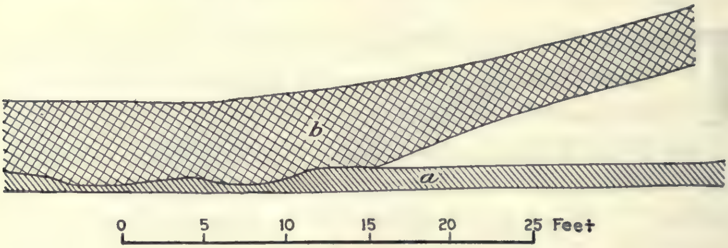


FIG. 156.—Pony Express mine, Ouray, Colorado. Horizontal sketch section showing split in vein. *a*, Barite-carbonate vein, gray copper, (ore runs 300 oz. silver); *b*, massive galena-blende vein of later period (22-27 oz. silver)—*b* incloses fragments of the black breccia veindike of the stage shown in Fig. 158.

I noted at the time of my examination, in 1909, that "the waters which formed the fluid part of the dike were probably the mineralizing solutions of the first stage of ore deposition; for some parts of the dike are impregnated by sulphides, and other parts have been pierced by subsequent veinlets of ore identical in character with the vein-filling which antedated the clastic dike intrusion" (Fig. 157). This forms a persistent and well-marked black breccia dike, well known to the miners under the name of the "Bachelor dike" (Fig. 158). The accompanying sketches were made in the mine workings.

Elsewhere in this group of mines, breccia injections of

the same age occur, but gray instead of black in color—gray because without the thick mud of black shale fragments

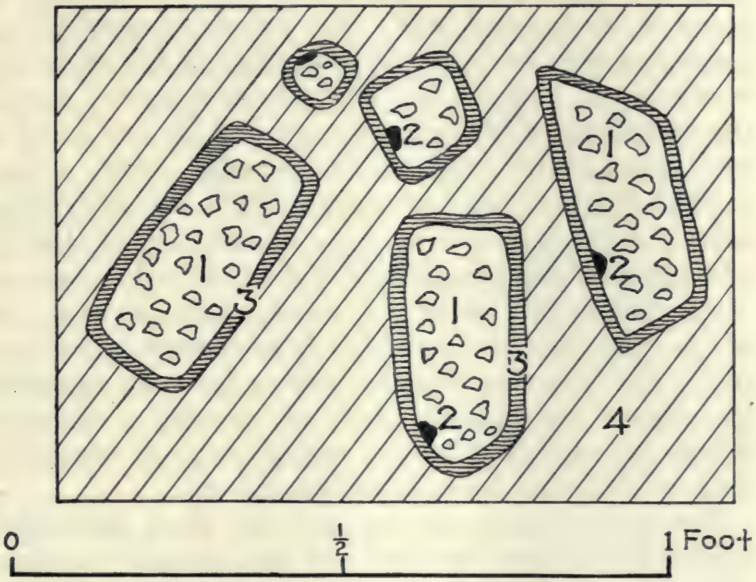


FIG. 157.—Pony Express mine, Ouray, Colorado. Detail from Fig. 158 on enlarged scale. Shows barite veinlet, later than breccia veindike, and cutting into it. 1, Breccia veindike fragments in veinlet; 2, gray copper on edge of No. 1 fragments; 3, fringe of red-brown carbonates around No. 1 fragments; 4, coarse barite, barren. This and Fig. 158 show the breccia veindike to have been intruded near the end of the first-period (barite-silver) vein formation.

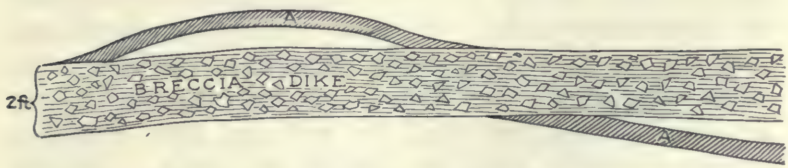


FIG. 158.—Pony Express mine, Ouray, Colorado. Horizontal sketch section, showing (*A*), first-period vein, six inches wide, of barite and mixed carbonates, containing tetrahedrite and chalcopyrite; very rich silver ore. This has been split by a two-foot silicified hard veindike of black breccia.

characteristic of the Bachelor dike. This gray breccia is hard, siliceous, and vein-like; and frequently, though not

always, occurs alongside of the veins; its habit shows that it is not a fault breccia, but an injection breccia, for it sends off, from its main dike fissure, sheets along bedding planes of the intruded rock. This was noted especially in connection with the Neodesha vein (Fig. 146 B), where the breccia is 3 to 10 feet wide. The breccia is barren; it contains fragments of the barite-silver ore, of the first metallic vein period, which occurs in the Neodesha vein; it also contains fragments of vein-quartz. Both the ore-bearing vein, and the later breccia vein, are affected by slightly subsequent horizontal slip-faulting along the bedding planes of the intersected, nearly horizontal, strata: so that the breccia must have been immediately subsequent to the spar vein. But later than this slip-faulting has been deposited the second metalliferous stage of vein-filling—massive blende, galena (low in silver), and pyrite; and veinlets of these sulphides are found in the breccia vein.

The gray siliceous breccia and the black shale-filled breccia of the "Bachelor dike" are then one and the same thing, the "Bachelor dike" differing as the result of an accident, which I have pictured above, and quite reliably, I think—the damming of the upwelling flood of this particular dike by a shale bed, and the final bursting through, with the consequence of the very unusual number of shale inclusions. There are two things to be noted about these breccia dikes, besides the fact that they are dikes, besides the circumstance that the gray breccias are hard and siliceous, and simulate barren veins, and that they are, indeed, veindikes. One thing, in the shale-bearing "Bachelor dike," is the fact that the included shale slabs are arranged parallel with the (sandstone) walls, indicating that the final pressure determining the orientation of these fragments was the pressure of the walls. This indicates a quiet or stagnant condition of the injected mud, after its tumultuous arrival, and before its consolidation. Also note that the carriage upward in this flood of fragments of soft shale of some size, from some underlying bed, without

entire breaking up and crushing, indicates a quite fluid condition of the whole mass.

The other thing I wish to note was observed in connection with the gray breccia in the Neodesha vein—that it contains pebbles rounded by attrition, and is like the similar "breccias" I shall describe at Idaho Springs (p. 853).

Let us consider a little further this Pony Express sequence before leaving it—and view the significance of the breccia injection. Its injection was as sharp and staccato an incident as the other vein injections here—first came the rich silver-spar vein—then the breccia injection—then the tail end of the rich silver-spar veins—then the slight horizontal bed-faulting—then the massive blende-galena-pyrite (chalcopyrite) veins. The breccia veins are unusual—the result of an accident, almost we suspect. The other veins represent the normal magmatic types, and the normal sequence, though inverted. What of the breccia veins, then? They are proved to be powerfully intrusive; they form straight parallel-walled dikes several feet wide. They come from below: the very fissures along which they and the veins occur never came to the surface: they stop at the base of a series of Tertiary volcanic beds called the San Juan tuffs, as shown by Irving's geological mapping of the general features of the district. Yet they were mainly detritus or mud—a fluid mud, as I have remarked above in connection with the shale fragments—a mud, in short, that acted much like a lava. Therefore, interest centers on the carrying element of the mud, the matrix of the paste. That it was siliceous is shown by the siliceous character of the cement, and the presence of primary disseminated sulphides in places indicates that it was a siliceous aqueous solution, with a little sulphide content. But it is as sharply distinct as black is from white, from the barite-silver solutions, into the latter part of whose injection period it was thrust. These, of themselves, have, in their clear-cut period, and their sharp type-individuality, the character of injections, much as has a dike of rhyolite or andesite. But they belong

to the ore types—the solution from which they formed was one of the characteristic ore magmas. The breccia vein-dikes are barren, and even the siliceous cement is scanty. Much or most of the carrying fluid of the mud must have disappeared during consolidation.

Therefore, I visualize the carrying fluids as highly heated siliceous waters and gases—not residual magmas, such as cause injection fissure-veins even of the barren-gangue minerals—even quartz—but aqueous-gaseous solutions. And I would correlate these solutions, in accordance with the theories I have arrived at previously (p. 831), as the residual waters and gases which are left over from the ore magmas, and which in this case were, I postulate, perhaps residual from the spar-silver ore magma which had mainly consolidated previously, as fissure veins. Ordinarily such residual waters—hot-spring waters—escape upward along fissures. But in these flat-lying strata, the fissures, as I have observed, which are characteristic of these brittle Carboniferous-Mesozoic sandstones, are interrupted and deflected by interbedded shales, and are largely quite cut off by the soft thick Tertiary San Juan tuffs above. Therefore the residual waters were pent back—and the power that they acquired as to intrusion was surprising—equal to that of an igneous dike-magma. Finally, had it not been for the "body" furnished by the mass of acquired inclusions, this aqueous-gaseous intrusion would not have remained as a dike—as the water and gases gradually escaped, the walls of the distended fissure would have again come together, and of dike or veindike probably little trace would have remained. But in this case, with the carrier fluid escaped, the included detritus of the mud remained as a "clastic" dike, a proof of what had taken place and of the power of pent-up hot water and gases.[2]

[2] Such a volcanic sand flowed from some now concealed fissure in the eruption at Katmai, in Alaska—flowed over the country in great quantity, and was so hot that trees picked up and carried on by it were reduced to charcoal.—Griggs: *National Geographic Magazine,* Oct., 1921.

How sharply does this point out the distinction between hot waters and the solutions (ore magmas) which have formed the mineral veins of this region and others!

While in the Bachelor breccia-dike the soft shale fragments were not destroyed by the movement of the intrusive mud, in the Neodesha breccia-dike hard fragments have been rounded to pebbles by attrition, showing the grinding of the sandy matrix during the upward motion and of one hard inclusion against another. An earlier agitation, pulsation, swirling or boiling of the sand grains is indicated, for the upward flow alone is insufficient to account for the results.

With the above data summarized, I wish to return to the Georgetown-Idaho Springs districts. The Mendota vein[3] is a fissure vein where a sulphide filling (blende and galena chiefly) has been injected into fissures, and this ore magma, as I have described (p. 130), held in suspension angular fragments of the wall rock. Locally, this sulphide vein, which lies in granite and gneiss, has been split open, and a crushed granite has been injected, which, cemented hard by silica, has a sufficiently close resemblance to the unbroken granite of the walls so that I at first mistook it for such in the mines. This crushed granite dike incloses large angular fragments of the blende-galena sulphide vein.[4] Curiously, as the sketch (Fig. 159) shows, this crushed granite injection has not so much formed a separate vein as it has demolished the old sulphide vein, within its own walls, and locally established itself within those walls. The crushed granite, as even the figure proves, is not due to grinding by faulting: the figure shows that it must be in the nature of a fluid injection; it is a fine, even granular, aggregate of unassorted granite sand, which, indeed, I recognized as surely fragmental only with the aid of the microscope. This material, I repeat, does not occupy a fissure—its longitudinal occurrence along the vein (and

[3] J. E. Spurr: *Professional Paper* 63, U. S. Geol. Surv., p 229.
[4] *Op. cit.*, p. 232, Fig. 71.

within its walls) is about 10 feet, and on both sides of this and between the same walls we have the solid sulphide vein. The injection, therefore, had a pipe-like form, and along it the displaced sulphide fragments must have been

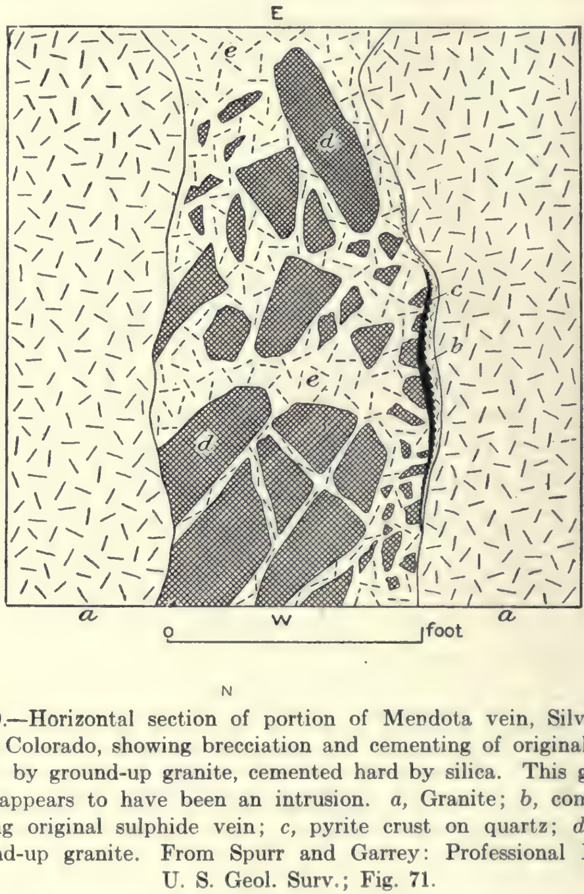


FIG. 159.—Horizontal section of portion of Mendota vein, Silver Plume district, Colorado, showing brecciation and cementing of original sulphide (blende) by ground-up granite, cemented hard by silica. This ground-up granite appears to have been an intrusion. *a*, Granite; *b*, comb quartz bordering original sulphide vein; *c*, pyrite crust on quartz; *d*, blende; *e*, ground-up granite. From Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Fig. 71.

carried far upward. Under the microscope the hard character of this finely ground granite sand is seen to be due to cementation by fine silica, fine crystalline to cryptocrystalline in nature. Here we have an occurrence like that of the "Bachelor dike," though with a different kind of rock forming the mud. Here, again, evidently the carrying aque-

ous fluid disappeared on consolidation; but that it was a siliceous solution, and without metallic minerals, is demonstrated; also that the bulk of the mud injection was very

Fig. 160.—Drawing, slightly under natural size, of specimen from section of Mendota vein, shown in preceding figure. *a*, Granite wall; *b*, comb quartz, first deposit in vein; *c*, finely ground granite, cemented by quartz; *d*, blende inclusions in ground-up granite. From Spurr and Garrey: Professional Paper 63, U. S. Geol. Surv.; Plate XLI B.

little different from that of the present hardened and solid granite-sand veindike. Figure 160[5] is a careful drawing, nearly natural size, of a specimen from this vein.

[5] *Op. cit.*, Plate XLI. B.

A similar occurrence was noted in the Buckeye mine, near Georgetown.[6]

In the Kirtley mine, also near Georgetown, a specimen of the vein-filling is a hard material which at first appearance seemed to be a fine-grained granite or granitic gneiss, but on close inspection proved to be finely crushed rock cemented by silica and barite. A veinlet of barite an inch and a half wide traverses the hardened granitic mud; and tabular barite crystals extend from the seam into the crushed vein rock, as if the barite veinlet had been formed while the crushed vein rock was still soft. On the barite crystals is, in many cases, a thin coating of quartz, which shades off into the quartz cementing the crushed rock. Earlier, however, than the crushed vein rock, are galena and blende, which occur in angular inclusions in it. This granitic mud vein of the Kirtley is, therefore, of the same period as at the Mendota; and the presence not only of quartz but of barite (and a little siderite) as cement shows that the aqueous carrying-material of the mud was allied to the vein phenomena. But the mud vein is barren: the hot waters which caused it were not the ore solutions of the district; and, therefore, I again postulate that they were the waters residual from the galena-blende ore magma, which waters have only succeeded in achieving a veindike because of the mud that they acquired through some accident.

Now, I wish to revert to the Idaho Springs side of the Georgetown Quadrangle. There are some peculiar "conglomerates" there, with rounded pebbles. Some geologists had told me before I examined the district that I should find "Archæan conglomerates" there. They were, however, plainly Tertiary phenomena, connected with the faulting, intrusion, and ore deposition. I found that these occupied fissures of slight faulting, and that the rounded pebbles were derived from the wall rocks; and I, therefore, called them "friction conglomerates" and attributed them to

[6] *Op. cit.*, p. 304.

a light rolling motion of the two walls of a fault fissure, so as to round the fragments of an original fault breccia. I have become, since then, however, somewhat doubtful of my interpretation, as I have never seen such "friction conglomerates" elsewhere as I recall, except locally in the breccia vein at the Pony Express mine, in Ouray (p. 847); and here it was apparently not a fault breccia, but an injection breccia. Therefore, I wish to go over the situation, citing especially again the Stanley mine, near Idaho Springs, where this feature was carefully studied. My explanation was a good one for the period: let us see if we have not advanced to a closer interpretation. A lot of events occurred at the Stanley mine, along the same slight fault fissure, one after the other. The country rocks are gneiss (varied in kind), and intrusive pegmatite. The first occupant of the Stanley fissure was a dike of bostonite porphyry. The second was a vein of sulphides and quartz (gold-silver ore). The third event was the injection of a latite dike. The fourth was the superposition, as it were, along the same fissure opened for the fourth time, of a zone or dike or vein of "a breccia, many of whose component fragments are subangular or even perfectly rounded, and which may, therefore, be called a conglomerate." The evidence is plain "that these rounded forms are due to the rubbing of one fragment against another . . . so that the deposits may be called a friction conglomerate. This conglomerate zone runs along the vein or along the porphyry and ranges up to several feet in thickness." "Large sections of the dikes and veins have been involved and mingled with fragments of gneiss in a heterogeneous mixture. As the exact plane of movement represented by this friction conglomerate did not always coincide with the earlier movements along this zone, the breccia in some places follows the contact of the ore or of the porphyry and in others cuts obliquely across these older formations, shearing them off."[7]

[7] *Op. cit.*, p. 346.

While I regarded this breccia zone in general as a peculiar type of fault breccia (it really occurs along a fissure of slight faulting, with a certain considerable horizontal component of movement), I nevertheless recognized that certain portions bore the marks of the infilling of open fissures by water-borne detritus. "Many such open fissures in the porphyry were filled by deposits which cannot be ascribed directly to crushing, but rather to infilling by water-borne detritus. The shape of these fissures indicates rending rather than shearing stress; yet the filling material is substantially of the same nature as other portions of the breccia zone where the materials have originated largely by grinding, and it is probable that the filling of the fissures was simply transferred by water from the supply of material due to attrition."[8] Figure 161[9] shows such a veinlet, which is evidently not a fault breccia; and of this figure I noted that the wall rock (latite) had been bleached "near the walls of the dike by the waters accompanying the plastic material which has been injected or squeezed into a fissure." What I thus rightly interpreted, and took to be an exception, I should, I believe, have accepted as a representative symptom, deciphering the nature of the whole; and this last is my present opinion. "Under the microscope the detrital veins filling the fissures in the porphyry show the general structure of sandstone or arkose, containing rounded, angular, or subangular grains of kaolinized feldspar, quartz, microcline, etc." This is similar to the sandy matrix of the breccia dikes described above at Ouray; but as the dikes at Ouray traverse sandstones, it might be inferred that they have derived their matrix therefrom; but here at the Stanley mine, at Idaho Springs, we have nothing but Archæan crystalline rocks and Tertiary porphyry dikes through which the breccia has come up; so that the comminution is indigenous, not exogenous; and is due to the dike forces. Under these circumstances, I can corroborate

[8] *Op. cit.*, p. 346.
[9] *Op. cit.*, p. 347, Fig. 132.

my earlier conclusion, whose significance I did not then fully grasp, that the Stanley breccia veins in general were due to grinding by friction: and that the friction was due

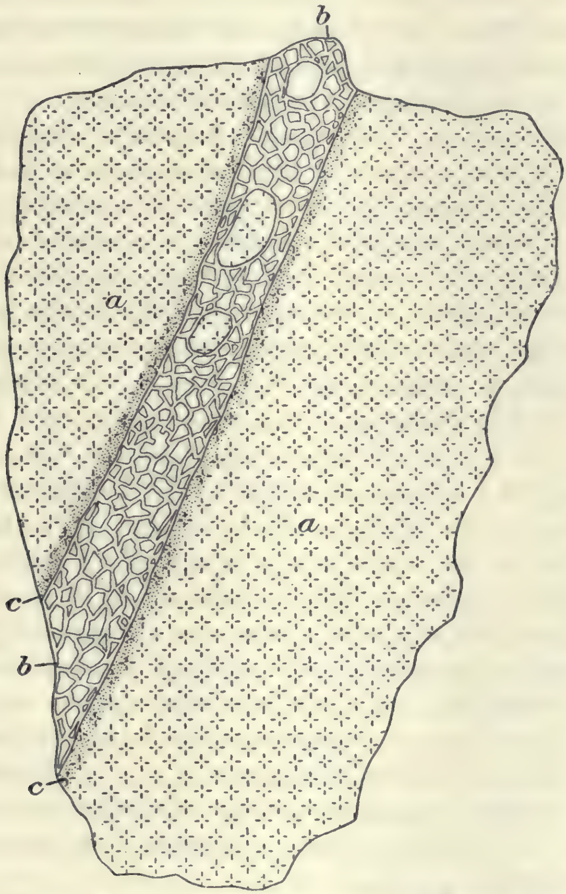


Fig. 161.—Sketch, actual size, of specimen from Stanley mine, Idaho Springs, Colorado. Shows small veindike (*b*) of assorted fragments of granite, gneiss, pegmatite, ore, and porphyries. This veindike is intrusive into biotite latite (*a*); *c*, slight alteration of latite on walls of veindike.

to the grinding of one included fragment on another. "The fact that the fragmental material along the veins in this region has been effected almost exclusively by rubbing of one fragment against another in the course of the main

movement shows that there has been practically no grinding stress, and that the movement, even if attended by faulting, was one of rending rather than shearing." But I did not visualize more concretely, as I am now warranted in doing from collateral data, that the attrition was due to boiling and grinding in a thick upward injected mud paste, borne by heated waters and probably gases.

Another thing. The Stanley breccia is cemented hard by silica "so as to form a rock that is in many places quite as hard and firm as the later porphyry or any of the wall rocks. Indeed, much of the hard, fine arkose is not distinguishable with great facility from some of the dense varieties of latite." I assumed this silica to be later than the friction breccia and injection veins of detritus; but now, with especial reference to the data in the Kirtley vein, above, and to the breccia veins at Ouray (p. 847), I believe it to have been contemporaneous with the vein injection, and that the waters which furnished the fluidity for the mud injections were siliceous. Note, above, that they have bleached the latite wall rocks; they were, therefore, probably hot. Moreover, they contained a little sulphides, though not enough to form any ore. "Here and there the arkose or conglomerate veins contain scattered or locally rather abundant sulphides, including galena and copper pyrite, which are not fragmental but have acted as interstitial cement to the rock fragments. . . . In the microscopic study it was observed that the sulphides had thus formed in an arkose veinlet which had been injected into the porphyry."

In general, however, the waters which accompanied these breccia injections accomplished little alteration of rocks, in contrast to the effect of the preceding ore solutions on the wall rocks, which resulted in an intense sericitization: frequently feldspar fragments derived from granite or pegmatite and included in these dikelets are nearly fresh. The injection, therefore, passed quickly; but the sparse sulphides are like those of the rich and concentrated ore period pre-

ceding, and I, therefore, again set up the explanation, as at Ouray (where the case is even stronger) that the waters and gases which bore up the hot mud were those residual from the ore-magma consolidation, though in this Stanley case a latite dike slipped in between, and therefore the hot waters in question may have been dike-magma residues.

A similar conglomerate vein, about three feet thick where seen, was noted in the Freeland mine, at Idaho Springs. "This material contains broken and rounded fragments of gneiss, pegmatite and ore, in a hard fragmental matrix. *The included fragments in general have the appearance of pebbles, being subangular and rounded like pebbles that have been rolled in a stream bed.*"[10] The different degrees of roundedness in the inclusions in these crushed rock dikes, from a sharply angular shape in the Mendota and Bachelor, to a perfect reproduction of stream pebbles in the Freeland and the Neodesha, show that in the same districts the amount of internal movement in the injections varied at different times, having evidently been greater where the inclusions have become rounded pebbles, and the matrix rounded grains. Indeed, they are, loosely speaking, "water-worn" pebbles, just as the pebbles in a stream bed are said (though, of course, not accurately) to be water-worn; and their origin must have been like that of stream pebbles, which are typically moved along, grinding on one another, in a thick emulsion of sand and water on the stream bottom. In the Freeland, also, as in the Stanley, there was a little sulphide in this breccia, though it is never ore; the main vein is older, and inclusions of it appear in the breccia; but there is no intervening dike, as there is at the Stanley.

[10] *Op. cit.*, p. 330.

CHAPTER XX

The Origin of Certain Ore Chimneys

This chapter recalls that the forms which ore magmas assume when intruded into rocks of the earth's crust have marked similarities with the forms assumed by rock magmas. Both intrude along fissures to form veins, veindikes or dikes; both penetrate along bedding planes to form sheets. Rock magma also intrudes as columns, pipes, or chimneys in which a cushion of gas precedes the lava. Does ore magma have the same habit? The phenomena at the Bassick and Bull-Domingo mines, in Colorado, indicate a gaseous explosion clearing a volcanic neck, followed by ore deposition: "The Patch," in Gilpin County, to my mind, indicates the same thing. These chimneys are filled with breccia or rounded boulders; but pipes like those of the Alice mine, near "The Patch," and the Jessie mine, at Breckenridge, showing only thorough shattering, are believed to be due to the same force.

IN HABIT—IN MODE OF OCCURRENCE—ores and gangues have (as I have repeatedly pointed out, although it really does not require much emphasis) numerous characteristics in common with igneous rock. For those ores and gangues which are intrusive, which have wedged into fissures under pressure, and for which I have accordingly suggested the term veindikes, this common mode of occurrence between veins and dikes needs, of course, no comment. Intrusions of igneous rock proper have much in common as to habit with ores in general; and the differences also are instructive. In both cases, the occurrence as long, thin tabular masses occupying fissures of slight fault displacement is the chief mode; and, therefore, the international confusion of nomenclature as to dikes and veins is natural. But ore and gangue material does not form the large intrusive masses that igneous rock does; it always occurs, where unmixed with country rock, or replacing it, in relatively narrow bodies. On the other

hand, there are many types of igneous rock which are characteristically quite limited as to size—these are the more highly differentiated types, like pegmatite, arizonite (p. 310) and many basic dike rocks. The very definition of the ore magma as an extreme type of magma differentiation connotes that the ore magma can never be gathered together in large masses, such as characterize the undifferentiated or half-differentiated igneous rocks. When we consider this we are surprised when we find occasionally, as we do at Aurora, in Nevada, true infilled fissure veins of quartz 100 feet wide between walls; and in many other cases veins 30, 40, or 50 feet wide; and we do not look for the occurrence of much more massive individual veindike injections.

Considering the inherent surgent or intrusive force (telluric force) which I have reasoned as a property of ore magmas (just as I have ascribed the possession of the same force to igneous-rock magmas), and which I have assumed to be gaseous tension, I have shown that rock magmas occur, when in small masses, preferentially as dikes because they avail themselves of pre-existing fissures—typically fault fissures of slight displacement, which have originated as a consequence of the strains involved in adjustments of position in the rocks. Not that they find these fissures yawning open, and simply rise to fill them—for certainly the walls of these slight fault fissures are usually closely pressed together—but the fact that the coherence of the rocks has been broken by these slight fault fissures renders these the lines along which it takes the least force to penetrate the rocks upward; hence the walls of the fissure are powerfully wedged apart by the insistently upwelling rock magma. In fissure veins the same explanation holds. In so far as these are plainly fissure fillings, it is in general as absurd to imagine original empty yawning fissures as in the case of dikes: not only were the vein walls thrust apart by the telluric pressure of the ore magma, but in many cases—in fact, typically—there is no evidence of gradual deposition, but of infilling at a certain definite catastrophic

period. Were it not for the pre-existing slight fault fissures, however, we should no more have dikes than we should fissure veins—they are fissure dikes, in short; and the *raison d'être* is the self-evident one that a force seeking outlet will choose the localities of least resistance.

Another evidence of this law, exhibited in the habit of igneous intrusion, is in the sending out of sheets or sills in sedimentary rocks along easily split stratification planes, which offer the same dynamic opportunity for easy passage as do the steeply inclined slight fault fissures. This habit is also exhibited in veins, and for very much the same reason. Upwelling rock magma also tends to be dammed back by impervious tough beds, like shales, tuffs, etc., and to spread out under them; upwelling ore-magma solutions have the same habit. I could cite many detailed instances in different districts where the same impervious beds had successively blanketed rock-magma and ore-magma solutions, and caused them to spread out in bed form below. Leadville offers one of numerous examples.

All this similarity, of course, does not imply that rock magmas and ore magmas are altogether similar: we know, of course, and the very definition implies, that they differ. Rock magmas contain water, but they are not aqueous or gaseous to any predominating degree; on the other hand, ore magmas appear to contain a variable amount of water and gases, whereby they are often highly penetrant and pass into solid rock and mix with it by impregnation or replacement, a property that rock magma, speaking broadly, does not possess.[1]

Besides fissure and stratification plane penetration, rock magma has another form of intrusion, which apparently depends upon a somewhat different principle—the igneous pipe or the volcanic neck. While a volcanic neck may depend for its localization on a complex intersection of fissures, as has, I believe, been suggested, I know of no evidence for

[1] Granitic and alaskitic magmas have this property in some degree and in some cases.

believing that this explanation is the true one. But I believe that there is every evidence of the truth of another explanation, which I have already advanced (p. 362). I have called attention to the fact that the deepest great intrusions—"batholiths" of granite and other deep-seated rocks—are broadly dome shaped; with rounded, irregular, or elliptical boundaries on a horizontal plane. Irregular or roughly dome-shaped intrusions of less horizontal area are, with dikes, characteristic of the igneous masses which have formed at more moderate depths, like the Tertiary monzonite intrusions of the region north of Idaho Springs and Central City, in Colorado,[2] or the intrusions at Matehuala,[3] Velardeña,[4] and the like, again with rounded, irregular, or elliptical boundaries on a horizontal plane. Finally, at the surface, we get intrusions of the same habit, with the same rounded, elliptical, or irregular boundaries on a horizontal plane, but covering a much less area than the porphyritic intrusions of the middle depths, just as the latter cover much less area than the granular intrusions of the greater depths: these intrusions at or near the surface are the volcanic necks or plugs, with which, when slightly denuded by erosion (as at Tonopah), we are all so familiar. Now, these volcanic plugs must reach a long way down, down to the differentiation zone, which is in the plutonic depths, for the lavas thrown out at the surface often represent differentiated magmas; therefore, some of the larger porphyritic intrusions of the middle depths must originally have passed into volcanic necks at or near the surface, while others, of course, died before reaching the surface; and in the same way some of the very deep-lying, areally extensive domes must have passed upward into the lesser intrusive columns of the middle depths, which again passed upward and terminated in volcanic plugs, and so spewed forth on the surface, while other of the deep-lying domes,

[2] See page 716, Fig. 136.

[3] See page 722.

[4] See page 768.

of course, died before reaching the middle depths. That is as far down as we can look, for the depth revealed by erosion is, after all, very limited, but the evidence of progressively greater areal extension of the great deep-lying domical intrusions in depth, where we can last glimpse these, does give grounds for the assumption that with sufficient depth they may join into one great couche, underlying large sections of continents surely, if not the whole continents and the whole seas. It is really difficult to postulate and visualize in detail the contrary.

We can at least reliably visualize the subterranean magma surface, solid or fluid, as reaching up somewhat like great stalagmites of lime from a cavern floor, some higher and some lower; but the comparison is not accurate, for some of the magma columns are oblique, and many are not round in cross-section, but elongated.

Why this column-like habit of intrusion? Apparently it does not always depend upon pre-existing rock-fissuring. In any magma surface at the ultimate depths, there are bound to be some slight differences or irregularities. I assume that the magma gases tend to accumulate more largely in the upward irregularities and that thereby (since I assume that intrusive potency is due to gaseous tension) these portions become more swiftly upward-working than the others. So a dome is a sort of blister, though the analogy must not be looked at too closely. As the magma reaches up in these domes, its ability to trap the magma gases becomes more efficient, and it becomes more acutely potent intrusively, the gases, we must assume, leading the way, and concentrating especially in the top of the dome, or upward-advancing plug. If this reaches the surface, there is frequently a great explosion as the compressed gases are relieved by access to the atmosphere; when the shell of crust above the up-advancing gas-bearing magma becomes too thin and weak, the gaseous tension blows out the stopper, breaking it into fragments and flinders, which, falling, form the explosive breccia that we

note as the lowest layer in many a volcanic accumulation. Behind this, the quieter lava wells forth from the chimney thus established. And before it blows off the stopper, how does it ascend? By force, certainly, just as it blows off the stopper by force—by shoving aside and up the solid rock. How is the solid rock shoved aside? That, the upworking magma column might say, is the solid rock's business: it may be accomplished by flowage, plication, faulting, all of which tend to be transmuted into a general element of uplift of the surface above, as I have earlier argued (p. 186). The dome, therefore, which tapers upward to a spire or plug, is the normal form of intrusion when the latter is not controlled by earlier fissures or other friendly preferential outlets.

Now, if many mineral veins are veindikes, which have gained their position by forcing open earlier fault fissures of slight or larger displacement, through the intrusive or surgent potency lent the ore magmas by the gaseous tension of the constituents, should not the ore magmas also occur occasionally along rudely cylindered pipes or chimneys, having bored a way upward through the solid rock, without the advantage of strong earlier fissures (p. 362)?

Let us investigate. A famous case or cases exist in Custer County, Colorado, which I have before described, but will now reinspect. The Bassick mine is in an "agglomerate" outcropping in a roughly square area between 3,000 and 4,000 feet in diameter (Fig. 162) and surrounded chiefly by solid Archæan granite and gneiss, together with intrusions (into the granite) of Tertiary volcanic rocks (andesite, trachyte, and rhyolite). This neck of "agglomerate" goes as deep as any explorations have been made (1,400 feet), and is almost vertical (Fig. 163). The material consists of unsorted angular and rounded fragments and boulders up to several feet in diameter, with the interstices between the larger fragments filled with smaller ones, down to the size of fine dust. The fragments are largely of andesite, with much granite and gneiss, and trachyte. It

is, therefore, younger than the Tertiary volcanics of the region, except for a dike of basalt (limburgite) which cuts the breccia ("agglomerate").[5] The "agglomerate" was interpreted by Emmons[6] and Cross as the filling of a chimney created by a gas explosion, which was not, as usual,

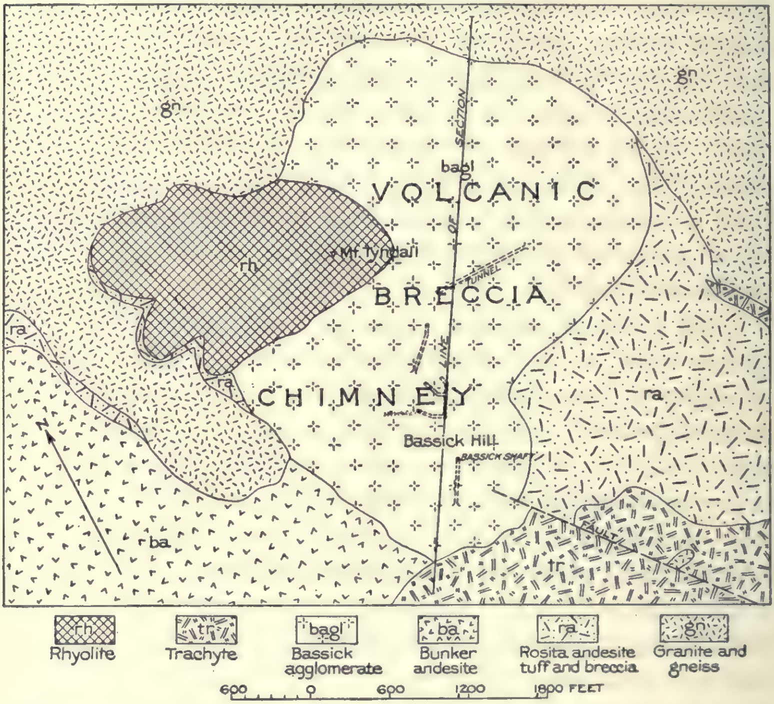


FIG. 162.—Surface plan of Bassick volcanic breccia chimney, the effect of a blow-out of volcanic gases. The blow-out was followed by ore deposition. Custer County, Colorado. After S. F. Emmons: *Seventeenth Ann. Rep.* U. S. Geol. Surv.; Part II, Plate XXXIII.

followed by upwelling lava. Immediately after the explosion, but before the subsequent basalt dike, there came a short sharp period of ore deposition, along a small pipe with elliptical horizontal cross-section, being nearly 100 feet in its longer diameter and 20 or 30 feet in its shorter;

[5] WHITMAN CROSS: *Seventeenth Ann. Rep.* U. S. Geol. Surv., Part II, p. 312.

[6] S. F. EMMONS: *Op. cit.*, p. 436.

and in depth extending more deeply than the mine went (1,400 feet). The ore consists of successive layers of sulphides on the boulders—sulphides of zinc, lead, copper, and antimony, with free gold, tellurides, and quartz. Emmons concluded[7] that "the ore deposition was here a phase of the volcanic eruption," and that it was due to fumarolic activity, due to water and other gases at a temperature of about 100° C. (Fig. 164).[8]

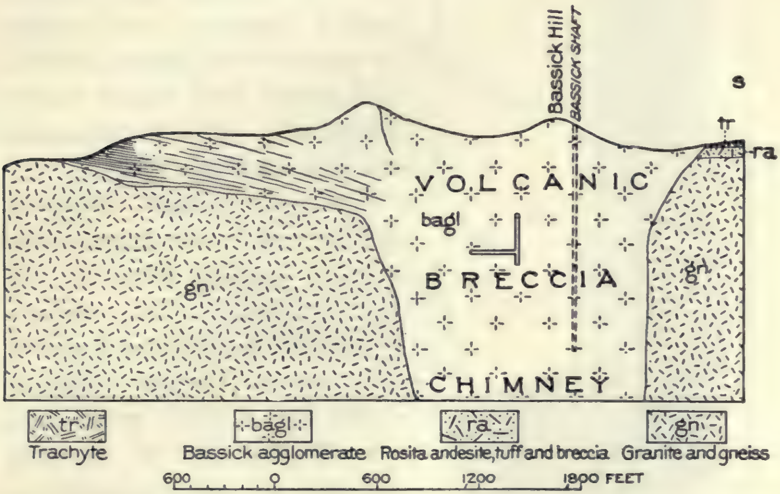


FIG. 163.—Vertical cross-section of Bassick volcanic breccia chimney, the effect of a blow-out of volcanic gases. The blow-out was followed by ore deposition. Custer County, Colorado. After S. F. Emmons: Seventeenth Ann. Rep., U. S. Geol. Surv.; Part II, Plate XXXIV.

Still more significant is the Bull-Domingo mine, several miles from the Bassick.[9] Here there is a pipe or neck of boulders entirely in the granite and gneiss; the pipe has a rudely elliptical horizontal cross-section, varying somewhat in horizontal area, but 40 by 90 feet on one level (Fig. 165). It was followed down, with no change in its average size, as deep as the mine workings went- -550 feet (Fig. 166). The

[7] *Op. cit.*, pp. 436, 437.
[8] *Op. cit.*, Fig. 40, p. 434.
[9] *Op. cit.*, Fig. 42, p. 442.

boulders are all of granite and gneiss "fragments that all were evidently once angular, but which, through some agency, have become more or less rounded."[10] As in the Bassick mine, the ore is in concentric layers around these boulders, but differs somewhat from the Bassick in mineralogical character, and consists of argentiferous galena, blende, and pyrite, with mixed earthy carbonates (of lime, magnesia, and iron) and quartz.

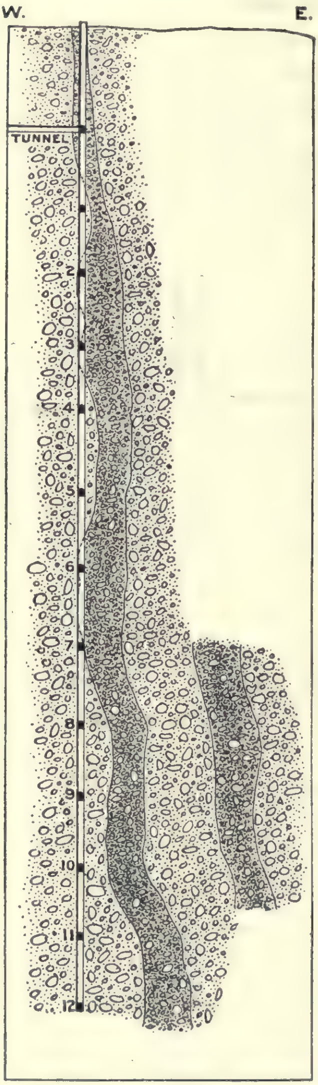


Fig. 164.—Bassick mine, Custer County, Colorado. Vertical cross-section of orebody. See text. After S. F. Emmons: Seventeenth Ann. Rep., U. S. Geol. Surv.; Part II, Fig. 40.

Curiously enough, Emmons did not apply his explanation of the Bassick mine to the Bull-Domingo, his reasons being that in the latter instance the nearest Tertiary volcanic rocks are a mile away, and second, that the ore minerals are such as are characteristic of "aqueous deposition," while he interpreted those of the Bassick as "deposited from gaseous solutions."[11] He therefore concluded that the Bull-Domingo pipe was formed by "a complicated intersection of a number of fracture planes, which produced a zone of broken country rock, in which the included fragments may have been somewhat rounded

[10] Emmons: *Op. cit.*, p. 443.

[11] *Op. cit.*, pp. 445, 446.

by attrition, but whose final rounding was more likely completed by the solvent action of percolating solutions. It seems quite possible that at the time explosive eruptions of igneous rocks were taking place in the adjoining regions by the force of such explosions heated gases or waters may

Fig. 165.—Bull-Domingo mine, Custer County, Colorado. Horizontal plan of orebody, at different levels, showing form of inclined pipe. See text. After S. F. Emmons: Seventeenth Ann. Rep., U. S. Geol. Surv.; Part II, Fig. 41.

have been injected through the fissures of the surrounding country rocks, and passing through this broken zone have, partly by attrition and partly by solvent action, rendered more complete the rounding of the rock fragments in this zone, and in that case probably have ejected some of them from near the then existing surface of the ground. As it is probable, however, that several hundred feet of rock

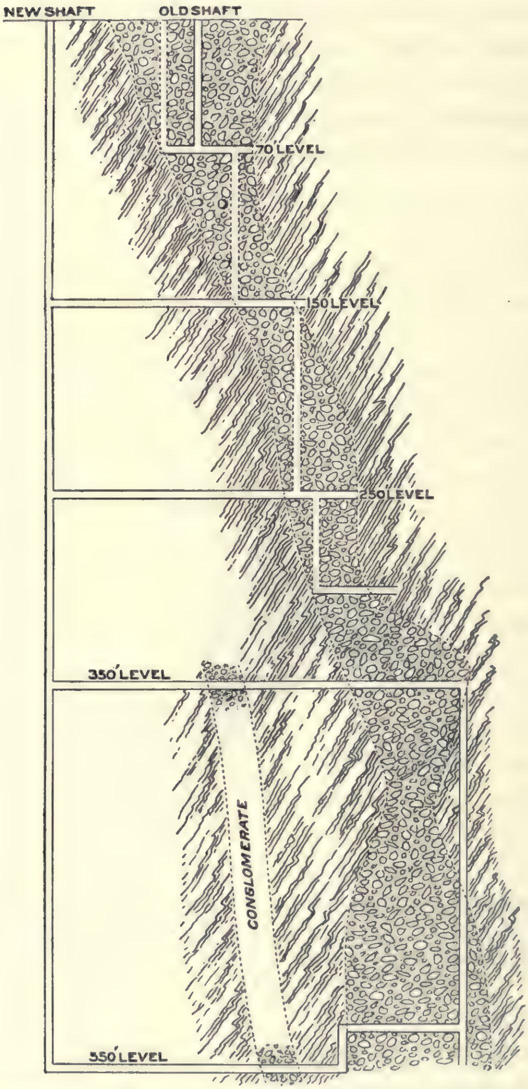


FIG. 166.—Cross-section of Bull-Domingo orebody, on line A—B of Fig. 165. See text. After S. F. Emmons: Seventeenth Ann. Rep., U. S. Geol. Surv.; Part II, Fig. 42.

material have been eroded off the surface since that time, it is not conceivable to me that they could have fallen back freely into such a narrow and intricate channel as this appears to have been." Emmons' difficulty lay plainly with the conception that the Bassick agglomerate was of ejected fragments which had *fallen back* into a crater, and he was logically unable to assign the same cause to the Bull-Domingo pipe, although his sections (Figs. 164 and 166) and descriptions indicate that the filling of the two occurrences is similar in physical characteristics. To my mind the Bull-Domingo case and the Bassick case together, near each other, and so unusual in type, form a better lesson than either taken alone. Each shows a pipe or chimney cleared through solid rocks, not by a lava intrusion, but by a gaseous intrusion—one pipe very large, the other very small. The boulders in the smaller pipe, certainly, as Emmons remarked, could not have fallen back after having been hurled heavenward, for the pipe is narrow and deep. For that matter, however, this imputed origin does not fully account for the Bassick agglomerate—namely, for the rounded "boulder" forms of the fragments, characteristic also of the Bull-Domingo pipe.

We are all of us familiar with volcanic breccias which are the result of explosive eruptions; the fragments do not have this frequently rounded shape, for in the Bassick agglomerate "some portions represent conglomerate as far as the shape of the fragments is concerned."[12] Clearly, these rounded forms are due to attrition, like any rounded boulders or pebbles; just as Emmons (above) recognized attrition as one of the boulder-shaping elements in the Bull-Domingo; and in still another mine in this same Custer County (the Twenty-six), where the orebody is a fissure vein in trachyte and andesite, he observes that "in the vein itself are boulders of andesite breccia and of granite, rounded by attrition";[13] and in this mine the ore has the

[12] WHITMAN CROSS: *Op. cit.*, p. 307.

[13] EMMONS: *Op. cit.*, p. 422.

banded structure of the Bassick and Bull-Domingo. The significance of all these occurrences (and others recorded in this county, which I will not detail) is obvious. The granite boulders mentioned in the Twenty-six mine are not fault-breccia boulders, for the fault-fissure vein is recorded as entirely in Tertiary volcanics; they have plainly been *brought up* from the granite below: that is, they form an upward-injected breccia or conglomerate, along the fault. Similarly, the Bull-Domingo "agglomerate" could not have come down, as Emmons pointed out; it must, indeed, have come up. And, although the Bassick conglomerate, near the surface, may have been ejected, and fallen back, it is similar to the other cases, and must have come up first, in much its present condition. The boulders in all these cases are due to attrition—and that attrition must have been the grinding of one fragment against another, as all were carried upward: the cases of the elliptical Bassick and Bull-Domingo pipes help us against the habitual thought of fault breccias. The propelling or carrying agent was probably gaseous-aqueous, as postulated by Emmons for the Bassick, where the period of agglomerate formation showed, as he observed, that it was a stage of the volcanic phenomena; but they were thin, like water and gas, and left little trace behind them. They were not the ore solutions, for in the Bassick the ore solutions followed immediately afterward, and formed an individual small pipe in the great barren breccia pipe. But the fact that they did form a pipe—a vertical pipe of rich ore in the great agglomerate—showed the kinship of the ore-magma surgent potency to that of the waters and gases which had formed the great "agglomerate" pipe, and that the ore-magma solutions also forced their way upward toward the surface by virtue of their gaseous tension. In the smaller Bull-Domingo pipe, the restriction of the ores to certain portions of the otherwise barren "conglomerate"[14]

[14] EMMONS: *Op. cit.*, p. 444.

points to the same conclusion: that the "conglomerate" preceded (immediately, as is shown in the Bassick by the basalt dike subsequent to the ore) the ore deposition.

In this district, therefore, where there is a succession of Tertiary volcanics, we have the interesting phenomenon that the ore deposition, which closed the volcanic sequence (except for the highly differentiated magma-type limburgite—see p. 864), was immediately preceded in at least two separate localities by barren aqueous-gaseous pipe intrusions, creating, in their passage upward through the rocks, a breccia or "agglomerate" chimney. Such gaseous-aqueous upward intrusions and explosions are a common phase of volcanicity; they are evidently wonderfully potent intrusively and surgently, and thereby confirm the potency of the gaseous tension of magmas to intrude; and they are usually followed by lava flows, indicating, I should think, that these gases—aqueous and otherwise—had accumulated at the top of a plutonic plug, working their way upward, while the lava followed behind. If this is the case, is it not fair to assume, in the case of the Bull-Domingo and Bassick, an upworking column or plutonic plug of ore-magma solution, aqueous and gaseous, at whose top the aqueous-gaseous components similarly concentrated; similarly, that when near the surface (within a few thousand feet of it) the gaseous-aqueous caps broke upward through the crust, leaving the ore-magma solution, analogously to the lavas in the common instance, to follow? And the narrow cylindrical channels of the following ore-magma solutions showed that these were of limited volume, as they were limited in point of time.

Of the same peculiar and characteristic type of ore chimney is, evidently, the Anna Lee oreshoot, at Cripple Creek, described successively by Penrose, Hills, and Lindgren and Ransome.[15] This ore chimney follows a basalt dike and extends downward at least 1,130 feet; it is nearly

[15] *Professional Paper* 54, U. S. Geol. Surv., p. 447.

circular in plan, varying from 15 to 30 feet in diameter "and extends nearly vertically, *but with a sort of corkscrew form,* into the earth. The core filling this pipe consisted of *well-rounded pebbles*[16] cemented together with material which is composed, for the most part, of the same rock pulverized." The ore is an evenly disseminated gold ore, higher in lime and iron than the other orebodies of the district (Fig. 167). While this orebody differs in character and in form from the other ores of the district, which occur as non-persistent fissure veins and impregnations, it seems to have been of the same period, since, like them, it apparently directly succeeded the basic dikes which closed the volcanic succession.

Of extraordinary interest, in considering this class of deposit, is the O. K. ore chimney in the San Francisco district of southern Utah, as described by Butler.[17]

The orebodies of this district followed directly upon the intrusions of Tertiary quartz-monzonite into Paleozoic-Mesozoic sediments. The deposits of the San Juan district in general are "more or less chimney-shaped"; but the most perfect example is the O. K. (Fig. 168), which "consists of a central chimney of pegmatitic quartz surrounded by altered and mineralized quartz-monzonite." Butler notes that in this district in general "the spaces occupied by the ore and gangue minerals were formed largely *by the solution of the rock* in the early stages of mineralization, and not by dynamic movement."

"In the O. K. deposit the solutions were apparently relatively confined and the dissolving action was strong, resulting in the formation of a more or less cylindrical channel, *with a maximum*[18] *dimension of fully 100 feet,*[19] now filled with quartz, some of whose individual crystals

[16] The italics are mine.—J. E. S.

[17] *Professional Paper* 111, U. S. Geol. Surv., p. 517.

[18] Horizontal.—J. E. S.

[19] The italics are mine.—J. E. S.

have a diameter of 10 inches and a length of 2 feet. The body as a whole strikingly resembles a coarse pegmatite,

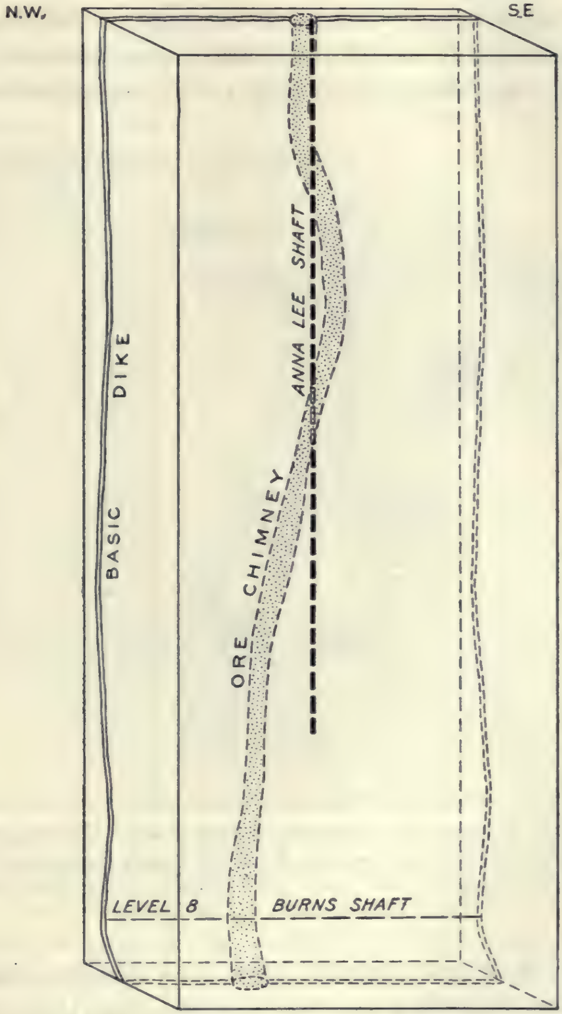


FIG. 167.—A cylindrical ore pipe. The Anna Lee ore chimney, in Cripple Creek, Colorado. See text. After V. C. Hills.

though no feldspar or mica is present. Sulphides are abundant in the main chimney only locally. . . . They are much more abundant in the small veins of quartz

extending from the main mass into the adjacent rock." The minerals are quartz, chalcopyrite, and pyrite, with some molybdenite.

The "small veins" referred to are seen in the stereogram as protuberant horns of the main quartz cylinder; moreover, they are shown as having a truly remarkable spiral-

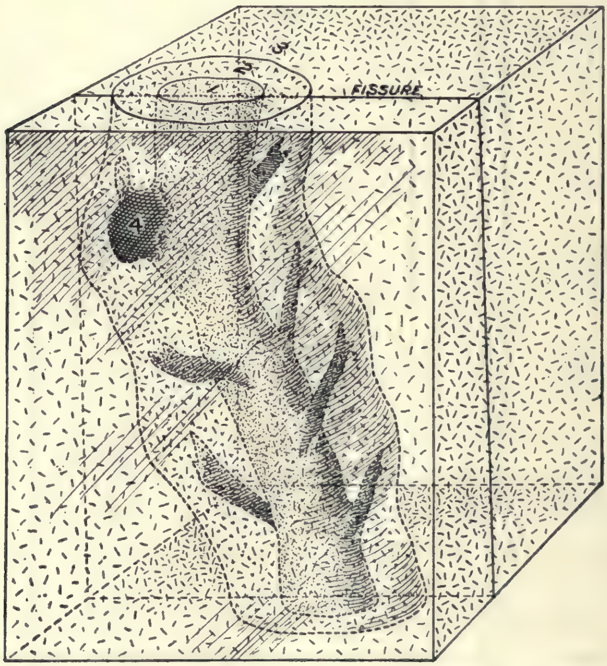


Fig. 168.—O. K. mine, San Francisco district, Utah. Generalized stereogram. 1, Pipe of pegmatitic quartz; 2, altered quartz monzonite; 3, quartz monzonite; 4, high-grade ore. After B. S. Butler: Professional Paper 111, U. S. Geol. Surv.; Fig. 54, p. 517.

like spacing, which, together with their uniform and regular upward as well as outward course, and their uniform and limited extension beyond the trunk cylinder, can hardly fail to be of great diagnostic significance. Indeed, the indications are that the solutions which produced the pipe were *revolving as well as ascending* in the narrow cylindrical channel, and the centrifugal motion accounts for the short

branch-pipes; in other words, it is suggested that the solution actually bored its way up.[20] What was this solution? Was it "hot-spring waters," which left a clean cylindrical hole a hundred feet in diameter, and of unknown depth—a hole into which the solutions which deposited the quartz rose, and which they cemented tight by precipitation? This explanation, I think, is out of the question. Such a great hole would have caved shut, even if left empty; every miner will bear me out in this; the pressure on the walls would have caved it. Butler does not mention any evidence of rubble in the chimney, as would be shown by a rock breccia, cemented by the quartz filling. It follows, surely, then, that the hole was bored by the ore magma which now fills it; and this proves anew the power of these magmas to bore up through solid rocks. The jacket of altered monzonite around the solid pipe shows the effect of aqueous solutions, residual upon its solidification.

Ore chimneys of argentiferous lead-zinc sulphides of considerable horizontal diameter (up to 100 feet or more) are characteristic of the mining camp of Santa Eulalia, in Mexico (See Chapter VII, p. 316). They have come up through limestone, and, unlike the examples which have been cited, are unusually tortuous, doubtless on account of the presumably easy solubility of the rock traversed. Such a chimney is shown in Fig. 169, projected somewhat to the plane of the section, so as to include in the section the whole of its corkscrew course. This pipe of ore, at a certain elevation, spread out far along a favorable limestone bed. Fig. 170 shows a projection, on a horizontal plane, of this flat portion of the orebody, showing that while the horizontal attitude was controlled by the bedding of the limestone (the limestone is not far from horizontally bedded), the linear extent was controlled by the prevailing vertical fracture system, the intersection of which with the limestone stratum produced the horizontal "run" or "shoot."

[20] This throws some light, perhaps, on the origin of the "corkscrew form" of the Anna Lee oreshoot at Cripple Creek, described above.

Next, let us inspect an ore occurrence described by Bastin and Hill in Gilpin County, Colorado, which is a hundred miles or so from Custer County, and in the same general region as some of the breccia veindikes discussed in the last chapter. This occurrence has been called locally "The Patch." "The origin of this interesting deposit has been the subject of much speculation and some controversy among mining men of the district. Structurally, it is a

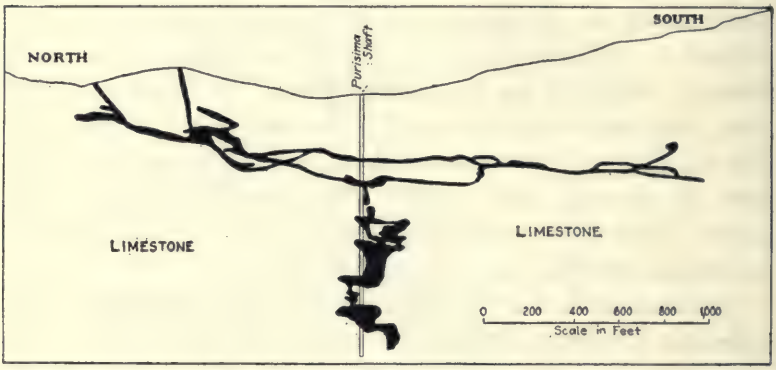


FIG. 169.—Mina Vieja ("the Old Mine"), Santa Eulalia, Chihuahua, Mexico. Projection, on vertical north-south section, of worked-out orebodies (oxidized silver-lead-zinc ores) in massive flat-bedded limestone (Mesozoic). Note chimney; also wide extension of flat oreshoots at favorable horizons above. But these flat oreshoots are due to the intersection of strong vertical north-south fissures with the favorable limestone layers. See Fig. 170. Ore is oxidized to bottom of chimney, a distance of over 1,200 feet below the surface.

body of irregularly fractured and brecciated rock. The degree of fracturing is variable. In some places the wall rock has merely been cut by an irregular network of fractures without much displacement; elsewhere it has been broken into fragments that have been moved over one another, many of them becoming rounded by friction and fragments of different kinds becoming indiscriminately mingled. . . . The brecciation reached a maximum along several northeastward trending zones that are parallel to and in some cases continuous with the veins entering

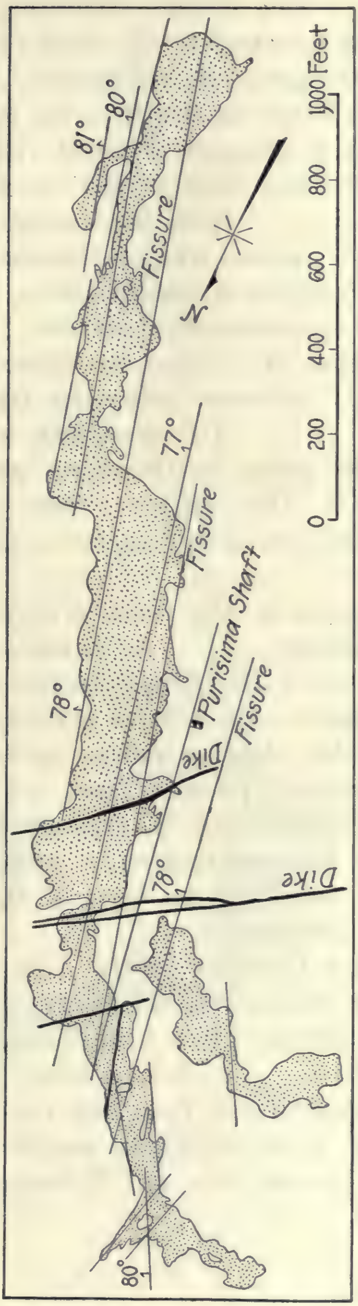


FIG. 170.—Mina Vieja, Santa Eulalia, Chihuahua, Mexico. Projection on horizontal plane of upper flat-lying oreshoots, shown in vertical section in Fig. 169. Note strong and regular north-south fissures, nearly vertical, whose intersection with flat-lying limestone layers has produced the oreshoot. Ore-magma solutions have ascended from below, along these fissures. Andesite dikes, later than the ore, are seen. No igneous rock older than the ore has been found.

'The Patch.' . . . 'The Patch' fracturing, therefore, appears to have been produced by the same forces and at the same time as the neighboring vein-fissures. . . . In surface outline, 'The Patch' as shown in the figure[21] (Fig. 171) is oval, having a diameter of about 750 feet from northeast to southwest and of about 400 feet from northwest to southeast. . . . From the surface down, the breccia of 'The Patch' persists without diminution in size, but with marked diminution in mineralization, to the Argo tunnel, a distance of approximately 1,600 feet. Its general form is, therefore, that of a 'pipe' or 'chimney' dipping steeply to the north. Its extent below the Argo tunnel is wholly conjectural. . . . The prevailing wall rock of 'The Patch' is granite gneiss, but in places bostonite porphyry is abundant."[22] The relations "show conclusively that the mineralization was later than the intrusion of the bostonite porphyry."[23]

As for ore, "some parts of 'The Patch' are barren; others are heavily mineralized. . . . As in the neighboring veins, the mineralization is of two types, one showing pyrite, chalcopyrite, and quartz with a little tetrahedrite as ore minerals, and the other showing galena, sphalerite, chalcopyrite, and subordinate pyrite. There is little intermingling of the two types. The ore minerals fill fractures and angular cavities between fragments, and also replace the silicates of the rock, and in most of the ore both processes have been operative."[24]

" 'The Patch' where traversed by the Argo tunnel, has yielded no workable ore, but the unusually complete and fresh section there afforded gives a clear insight into its nature and origin. . . . In places along the tunnel, 'The Patch' is a breccia of rock fragments not larger than four feet in diameter, in an arkose-like matrix. The frag-

[21]Bastin and Hill: *Professional Paper* 94, U. S. Geol. Surv., Fig. 36, p. 235.

[22]*Op. cit.*, pp. 96, 97.

[23]*Op. cit.*, p. 235.

[24]*Op. cit.*, pp. 96, 97.

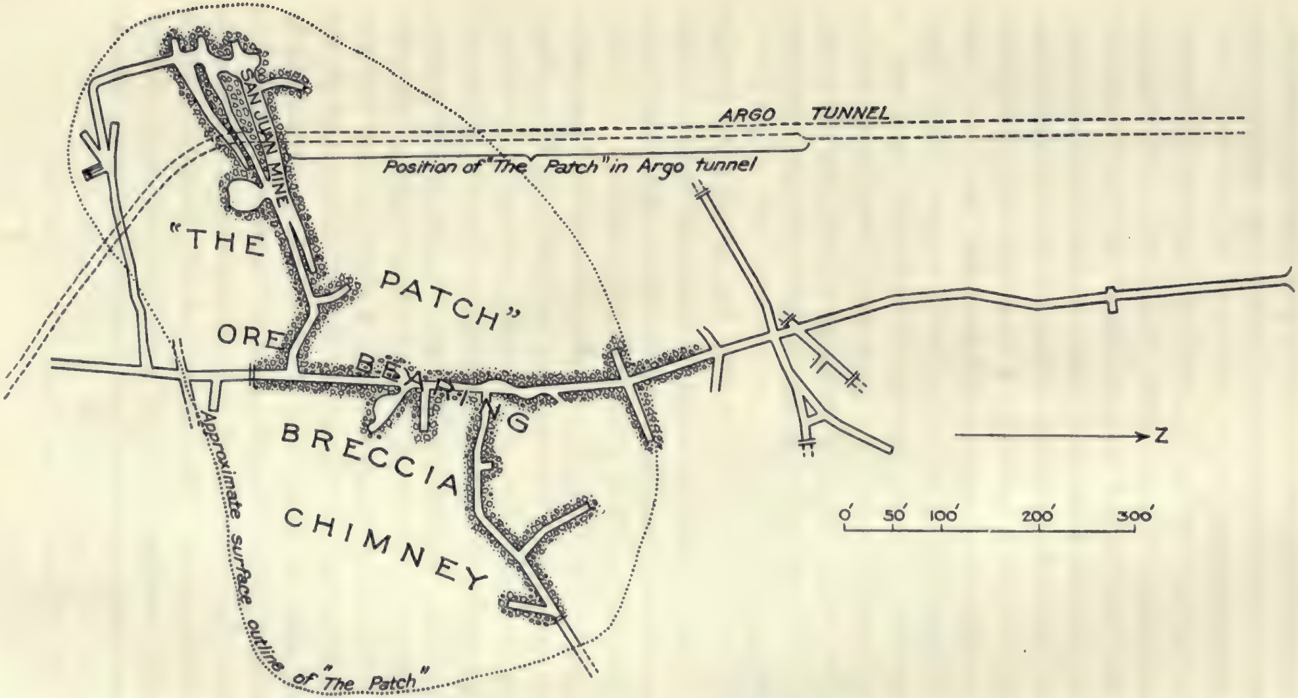


FIG. 171.—Horizontal plan of "The Patch" breccia chimney, Gilpin County, Colorado. This chimney is propably (J. E. S.) due to a blow-out of volcanic gases. The blow-out was followed by ore deposition. After Bastin and Hill: Professional Paper 94, U. S. Geol. Surv.; Fig. 36.

ments are heterogeneous in size, in lithologic character, and in degree of rounding, most of them being angular and a few perfectly rounded.[25] . . .

"The Gardner vein as exposed just west of 'The Patch' is a sharp-walled fracture filled with pyrite and chalcopyrite. As 'The Patch' is approached the vein sends off branches into the walls, and these branches break up within a very short distance into a network of very small veins traversing the wall rock in all directions and dividing it into a multitude of angular blocks which have not, however, undergone much movement with respect to each other. This network of veins passes into 'The Patch,' composed of angular fragments that have been more or less moved upon each other, the interspaces being partly or wholly filled with ore minerals and the fragments themselves partly replaced by sulphides."[26]

About 2,000 feet north of "The Patch" lies the Hubert mine, which worked a series of east-west fissure veins. "One of the most instructive parts of the mine is the large stope near the west end of the 850-foot level. . . . The vein begins to split up and eventually forms a network of sulphide stringers traversing the gneiss in all directions; this passes locally into a true filled breccia (Fig. 172).[27] The fragments have plainly been moved from their original position. The largest are not more than three inches in diameter and most of them show sharp angular outlines. . . . The ore breccia extends upward to the 700-foot level, but apparently does not extend downward to the 950-foot level, the vein . . . in that level branching in a normal manner without notable brecciation. The ore breccia of the Hubert mine is identical in appearance with certain portions of 'The Patch,' and was probably formed by similar processes acting on a much smaller scale. Stress initiated along the South vein fracture and along several

[25] *Op. cit.*, p. 236.
[26] *Op. cit.*, p. 237.
[27] *Op. cit.*, p. 97, Fig. 6.

branches leaving it at nearly the same point apparently became more or less distributed through the intervening rock, fracturing it irregularly and in places moving the fragments among themselves. This fractured and porous mass became a favorable locus for ore deposition. The underground workings and the ore on the dump and in the bins show that the great bulk of the sulphides were deposited in open spaces, either in cracks or between the fragments of a breccia. . . . The ore of this mine is entirely of the galena-sphalerite type."[28]

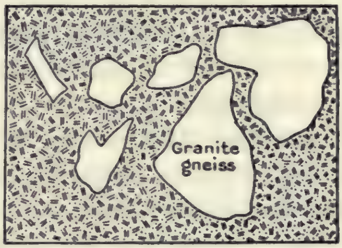


FIG. 172.—Sketch of filled breccia in Hubert mine, Gilpin County, Colorado. Angular fragments of granite gneiss lie in matrix of galena and sphalerite. One-half natural size. After Bastin and Hill: Professional Paper 94, U. S. Geol. Surv.; Fig. 6.

Taken altogether, these are extremely valuable observations. "The Patch" is an elliptical chimney of breccia and boulders rounded by attrition, extending down to the lowest depths (1,600 feet) explored, and apparently quite similar to the Bassick and Bull-Domingo "agglomerate" chimneys, and intermediate in horizontal diameter between the two. The ordinary fissure veins of the region pass out of it, or into it, and the sulphide ores which fill the fissures are continuous with the sulphide ores which cement the breccia and agglomerate of the chimney. The instructive minor type of the Hubert mine shows a similar small chimney with a sulphide-cemented breccia, formed at the junction of branching vein fissures, and apparently passing into a normal forking fissure vein below. But the "true filled breccia," of which a drawing is given by Bastin (Fig. 172) incloses in a blende-galena matrix angular fragments of rock so widely separated that it must be they were supported free in the sulphide magma when the latter was fluid, in practically its present form of concentration, and

[28] *Op. cit.*, p. 220.

that the sulphide magma was an intrusive magma. If you will examine the two largest fragments of gneiss in the sketch, you will see that they have apparently been split from one another by the blende-galena matrix. Therefore, the cavities which were filled by the sulphides were not—could not have been—pre-existing; they were synchronous with the sulphides, and formed by their intrusive force. The phenomenon is, therefore, identical with that described by myself in the Mendota and other veins at Silver Plume, where both the sulphide matrix and the included fragments of wall rock are similar to the Hubert occurrence. Only at Silver Plume the ore is confined to the fissure vein, showing, as I pointed out, the intrusive character of the fissure-vein filling; and in the Hubert the same type of intrusive fissure-vein filling breaks locally, at a vein-forking, into an intrusive chimney, a difference of form only.

The regularly curved elliptical horizontal outlines of "The Patch" agglomerate-pipe and its regular chimney-like downward extension, do not, in my opinion, lend support to the theory of an origin by the intersection of fissures; moreover, the map does not show any series of fissure veins there converging, while there are numerous areas of complex vein intersection shown on the same map, which have given rise to no breccia pipe at their intersection. The dynamic origin of this chimney seems to me, from all evidence, plainly a local one, not exhibited elsewhere in the mapped area; and it seems to me plainly a blow-out of gaseous accumulations. The physical results are the same as in the Bassick and Bull-Domingo pipes—thorough shattering, brecciation, and in places such tossing and rolling around, and upward movement of jumbled blocks that they become completely rounded, and embedded in the finer detritus (arkose) worn from their broken edges.

The fact that by no means the whole of the chimney has been filled with ore shows that it was not the ore solutions, gaseous or otherwise, whose accumulation blew out the plug; but it was the *avant-coureur,* or gas cushion, as in

Custer County. The ore solutions followed. Moreover, the two types of metallic sulphide stages, found as fissure-vein fillings of distinct age throughout this whole belt from Silver Plume to Boulder County, were also injected here; and also here separately, for Bastin records that there is little mingling between the two types. This affords a valuable insight into the ore history of the whole belt; for it shows that the two ore-magma stages did not depend entirely for their sequence on dynamic accidents such as the fault-fissuring; for in this pre-ore breccia chimney the ore-magma ascensions were of the same two definite succeeding stages as in the fissure veins, meaning that the impulse or initiation of each of the ore-magma upward migrations was in the magma below, just as it was in the case of the initial gaseous explosion which cleared the road. An accumulation of ore magma in the depths, in each case, till the necessary surgent potency—namely, the necessary gaseous-tension pressure—had been attained, sufficient to allow it to force its way upward, either along this breccia pipe, or (as ordinarily) along slight fault-fissure channels to form veins, is clearly indicated—two periods of such ore-magma accumulation, separated by a considerable period of time as we measure it, but, geologically speaking, very close together. And when these ore-magma gushes did arrive, they were truly potent surgently, as is shown in the little Hubert chimney, which is an intrusive body of the second ore-magma type; and as is shown not only in the connected Hubert fissure vein but in a hundred other fissure veins as well—such, for example, as the Mendota.

One can hardly avoid the explanation of the intrusive (surgent) cushion of gas from the magma, which created breccia chimneys like the Bassick. In assigning this to a gaseous emanation, Cross[29] cites similar gas-volcano Carboniferous chimneys in Scotland, as described by Archibald Geikie: "The cross-sections of the vents are usually circular or oval, with varying irregularities, and in size they

[29] *Seventeenth Ann. Rep.*, U. S. Geol. Surv., Part II, pp. 310, 311.

vary from a few yards to more than a mile in diameter. The filling of the vents is in numerous cases entirely fragmental. . . . Certain channels are almost wholly filled with fragments of the rock through which the orifice has been forced, others contain varying amounts of eruptive rock fragments, and some are almost free from debris of the country rock. The explosive force seems, therefore, to have preceded the column of molten matter, and if the latter did not reach the surface and the action was not renewed the channel became filled to some depth with fragments of wall rock."

The extensive erosion which has taken place in the Central City area indicates that a great deal has been eroded from "The Patch" breccia chimney. It is altogether likely that this extended quite to the surface. Bastin estimates that there has been between 7,000 and 11,000 feet eroded, and hazards the conjecture that the ores were deposited at temperatures between 150° and 300° C;[30] while Ball, for the Georgetown district, estimated the depth of the column of rock removed by erosion as between 4,500 and 5,250 feet or more.[31] Therefore, the present cross-section of the chimney exposed on the surface is a mile or two below the original vent.

The transition from fissure-vein fillings to chimney-breccia filling described by Bastin is important. It does not prove that the chimney is simply a case of intersecting fractures; it indicates nothing of the sort. It does lend great strength to the explanation of the filling of fissure veins by injection. There is a very long and strong fissure vein which runs into "The Patch" chimney; and it may well be that the chimney is localized along the fissure because of the fissure, and the facility it afforded for surgency. Similarly, lava eruptions are frequently found along fault fissures, like the basaltic cones at the east base of the Sierra Nevada, and like the little craters of the moon,

[30] *Professional Paper* 94, U. S. Geol. Surv., p. 134.
[31] *Professional Paper* 63, U. S. Geol. Surv., p. 145.

which in the photographs may be seen to be lined up along fault fissures. Many of these moon craters are evidently the result of gas emissions only.

One other point we must recall, before leaving "The Patch." Its entire breccia filling is like the "breccia lodes" or "friction conglomerates" (Chapter XIX), which I have described along vein fissures, representing a certain stage of the fissure history, and in the cases noted—the Stanley and the Freeland—the last stage (post-ore). I have described these occurrences as fissure injections, but with apparently water and some silica; therefore, as "The Patch" breccia is pre-ore, we have the same "friction conglomerate" developed at different stages.

The different stages or volcanic occurrences of this Idaho Springs region may then be summarized: 1, Slight systematic fault-fissuring; 2, first intrusion of dikes (chiefly monzonite and bostonite); 3, slight fault-fissuring; 4, first gaseous intrusion and eruption, creating "The Patch" orifice; 5, first (pyritic-gold) sulphide invasion; 6, second (galena-blende) sulphide invasion; 7, second (minor) dike intrusion (latite, etc.); 8, second aqueous-gaseous intrusion, bringing in breccia conglomerates (and interstitial arkoses) along fissures (Stanley mine).

The arkose injections which inclose fragments of the ores (p. 849) are of the same stage as the post-ore breccia lodes, and are simply finer-ground.

"Sandstone" dikes evidently are often of the same type; they have been described in many localities. One group represents intrusive hot waters and gases, laden with debris.

The Alice mine is a number of miles distant from "The Patch." I am familiar with it, having done some development work over a period of several months, and much sampling with a view to purchase. I quote Bastin's description[32]:

"The deposit is not of the vein type, but constitutes a large irregular body of more or less mineralized rock."

[32] *Professional Paper* 94, p. 323.

The rocks near the mine are Archæan gneiss, and intrusive monzonite and alaskite porphyries, the latter forming the wall rock of the ores. "Typical fissure-vein mineralization, so common in this vicinity, is represented in the Alice mine only on a small scale by a few straight and persistent pyrite veinlets. . . . The important mineralization has been accomplished through the removal in solution of certain constituents of the porphyries and the deposition in their places of metallic sulphides, or, technically speaking, by metasomatic replacement which was initiated along a net-

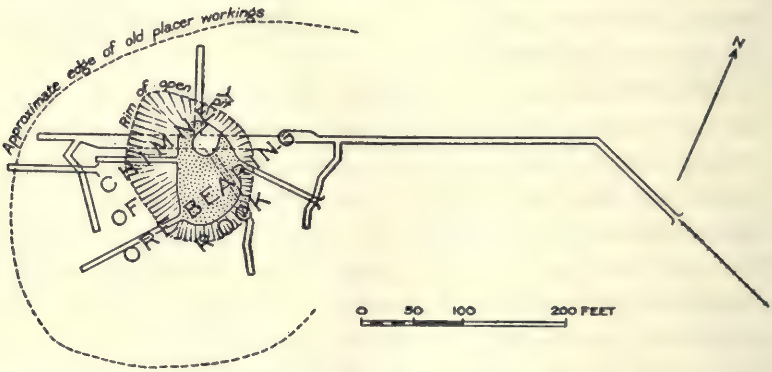


FIG. 173.—Horizontal plan of Alice ore chimney, a chimney of shattered porphyry impregnated by pyritic ore. Clear Creek County, Colorado. See text. After Bastin and Hill: Professional Paper 94, U. S. Geol. Surv.; Fig. 66.

work of irregular fractures. . . . Mineral-bearing solutions similar in character to those which deposited the typical pyritic veins of the Alice district were the mineralizing agents, but instead of penetrating along straight and open channels they worked their way through a network of minute crevices formed by the irregular fracturing of a large body of porphyry. The cause of this fracturing is unknown, but it is not unique in this general district, similar fracturing being observed in the Commercial Union mine, near by, and on a more extensive scale in 'The Patch.'"

As will be observed, there is no breccia, no agglomerate at the Alice mine; only a network of fractures. Is it justifiable, then, to compare it with "The Patch" agglomerate pipe? One thing is significant—the apparent nearly circular outline of the ore—in which the chief values (which are low) are in gold and copper. If the ore goes downward with the same cross-section, we do have an ore chimney here—something like 300 feet in diameter (Fig. 173).[33]

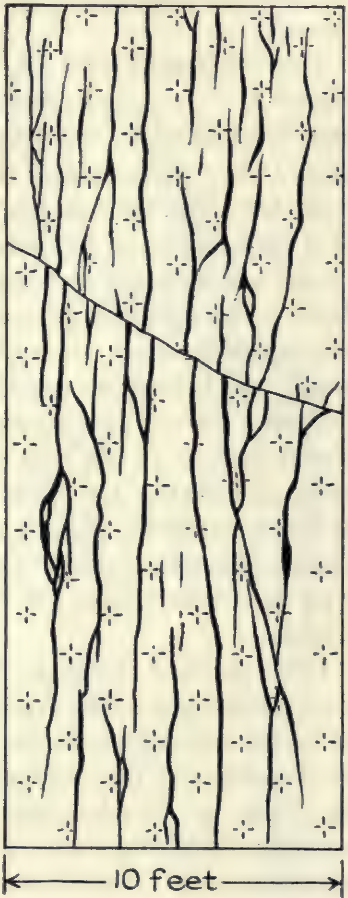


FIG. 174.—Sketch of stringer lode in Jessie mine, Breckenridge, Colorado. After F. L. Ransome: Professional Paper 75, U. S. Geol. Surv.; p. 146.

The above occurrences are called by Bastin "stockworks." Ransome has also described some "stockworks" on this same mineral belt, at Breckenridge, Colorado[34]: "A distinctive feature common to these deposits is the occurrence of the ore in much-fissured and minutely veined rock (ordinarily quartz-monzonite porphyry), rather than in well-defined lodes. . . . At the Jessie mine a mass of porphyry, oval in plan, fully 900 feet long, 600 feet wide, and 300 feet deep, has been fissured in many directions, but especially by fractures striking from east to northeast. The whole is thus a low-grade stockwork; but mining has in the past been confined to those zones in which the fissures

[33] *Professional Paper* 94, U. S. Geol. Surv., Fig. 66, p. 324.

[34] *Professional Paper* 75, U. S. Geol. Surv., p. 143.

are closely spaced (Fig. 174). . . . There is no great persistency to these lodelike zones of stringers. Some die out within surprisingly short distances, or merge with other zones."

The horizontal plan of the Jessie orebody is given in Fig. 175.[35] It is oval, like the Alice described above, and like "The Patch"; but physically it is like the Alice, 30 miles away. What causes the elliptical outline of the Jessie orebody? Not the monzonite. This is only on the borders of a very extensive monzonite intrusion in the Cretaceous shales, a mile wide, and much longer. It is, then, like the Alice, a complicated, intense strain zone due to some force which acted nearly vertically (the fissuring is nearly vertical), just before the mineralization, which was essentially of pyrite, blende, and galena, accompanied by sericitization of the rock, as in the case of the Alice. The depth of the body, like that of the Alice, has not been determined, but, so far as explored, in both cases the ore has the form of a nearly cylindrical pipe. There are other orebodies of this type at Breckenridge, but they have never been carefully mapped.

I feel inclined to accept Bastin's view of the close physical relationship of the Alice to "The Patch," just as I feel still more strongly as to the relationship of "The Patch" to the Bassick and Bull-Domingo pipes. The Alice mine and the Jessie, at Breckenridge, appear, then, to be pipes of complex fracturing—not brecciation; far less of friction conglomerates. But they seem to mark the beginning or first stages of the physical disturbance along a cylindrical pipe of rock, which carried further or done more intensely would result in an agglomerate chimney; and, indeed, parts of "The Patch" chimney, according to Bastin, also show these first stages. If the origin of all of these is alike, we must ascribe these cylindrical fractured chimneys like the Alice, and the Jessie also, to the passage upward from below of a gaseous eruption—in these cases not so violent

[35] *Op. cit.*, p. 145, Fig. 18.

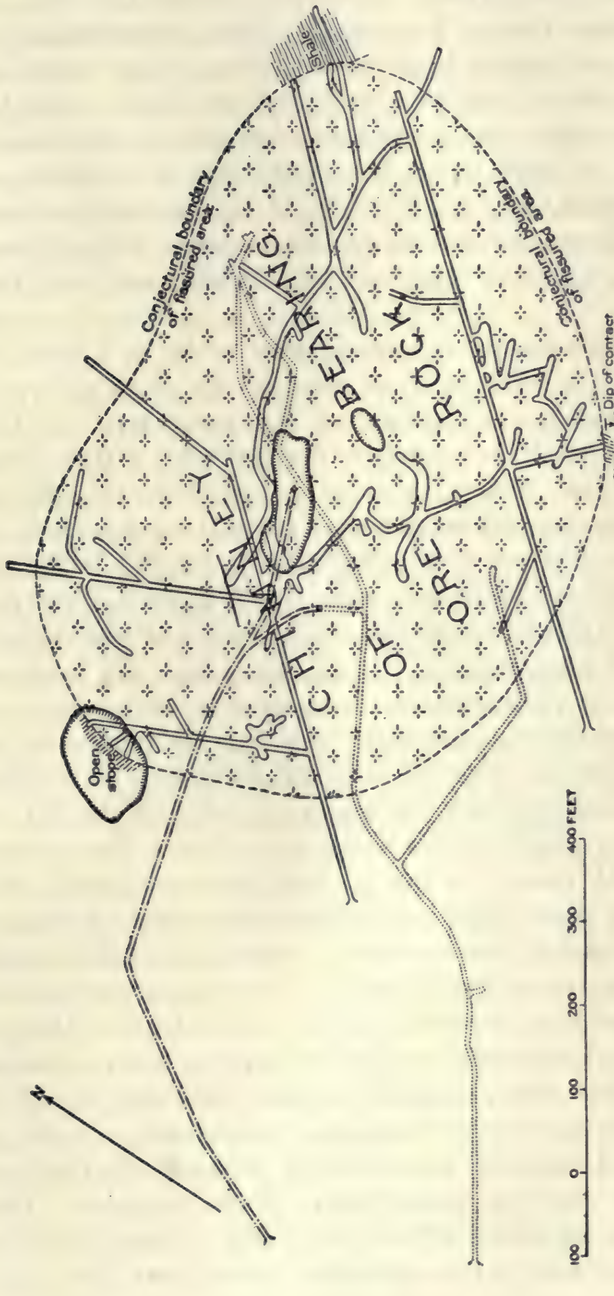


FIG. 175.—Horizontal plan of ore chimney of Jessie mine, a shattered portion of a Tertiary quartz monzonite porphyry intrusion; Breckenridge, Colorado. After F. L. Ransome: Professional Paper 75, U. S. Geol. Surv.; Fig. 18.

as in the case where, ultimately, jumbled breccia and agglomerate result. But the effect has, nevertheless, been intense and highly localized fracturing, along which sulphide solutions later rose, and produced, both at the Alice and the Jessie, what is commonly known as a disseminated deposit. In both mines, the whole mass is low-grade ore, very difficult to mine selectively. I have visited the Jessie: I should consider the term "disseminated deposit" more accurate, or more modern, than "stockwork" for these deposits.

The disseminated copper deposits, so far as I have seen them, are at least in some cases of the physical type of these disseminated deposits of the Jessie and the Alice. The only one I am intimately familiar with is Ray. I will not, however, attempt to show an origin for the Ray primary orebodies like what I have inferred for the Jessie and the Alice, but will note a few data to consider. The Ray body is an elongated belt, over 10,000 feet long, and from 1,000 to 3,000 feet wide, in which the schist and intrusive bodies of granite porphyry have been intensely fractured, followed by impregnation throughout (replacing the rock, and especially forming along the fracture planes) of cupriferous pyrite. This belt is underlain directly by the slope of a granite batholith, subsequent to whose upheaval into this schist terrane and to whose consolidation the ore deposition took place. In the ore belt there are certain areas relatively more highly mineralized than others; and one of the principal of these occurs in, over, and around a small upreaching protuberant detail of the batholithic mass of granite porphyry beneath; so that the evidence of the close connection, genetically, of granite porphyry and primary ore is excellent. Now, since the complex fracturing which has afforded a site for ore deposition characterizes both porphyry and schist, the stresses which produced the fracturing obtained after the consolidation of the intrusion. What these stresses were I will not undertake to guess; they may have been due to the adjustment throughout the cooling

magma. On the other hand, we have seen that such adjustments characteristically produce fissure veins. They may have been due, also, to a general upward escape of magmatic gases, accumulated under this area. The general intense, non-localized fracturing, and the relatively local character of the elongated patch of mineralization, would not be out of harmony with this latter explanation. These mineralized disseminated copper areas are rarely found, though regions where the apparently requisite geological combinations occur are widespread.

"It would be a mistake to believe that a science consists of nothing but conclusively proved theorems, and any such demand would be unjust. Only a person with a mania for authority, a person who must replace his religious catechism with some other, even though it be scientific, would make such a demand. Science has but few apodeictic precepts in its catechism; it consists chiefly of assertions which it has developed to certain degrees of probability. It is actually a symptom of scientific thinking if one is content with these approximations of certainty and is able to carry on constructive work despite the lack of the final confirmation."

—SIGMUND FREUD.

INDEX

The Roman figures refer to pages in the first volume; bold-face figures to pages in the second volume.

B

C

D

E

F

H

M

N

O

Q

R

T

U

Y

Z